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EXPERIMENTAL INVESTIGATION FOR ENHANCING THE FLEXURAL AND SHEAR CAPACITY OF RC BEAMS USING GLASS FIBER REINFORCED POLYMERS AND CARBON FIBER REINFORCED POLYMERS

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ABSTRACT: This study deals with experimental investigation for enhancing the flexural and shear capacity of RC beams using Glass fiber reinforced polymers (GFRP) and Carbon fiber reinforced polymers (CFRP). Fifteen concrete beam specimens with dimensions of 110mm width, 200mm height and 1300mm length were fabricated in the laboratory. As per practical consideration of pre-stressed bridge girders, one 30mm diameter longitudinal hole was provided below the neutral axis in the tension zone in all the beams for future strengthening, service lines and other consideration. The geometry of all beams was kept constant, while steel reinforcement varied as per initial design. Out of 15 beams four were control beams. One beam was made without any steel reinforcement strengthened with two layers of GFRP fabrics U- jacketed over the full span. Five beams were weak in flexure, strengthened using GFRP fabrics with varying configurations in higher flexural zone. Four beams were weak in shear, (tied with two 6-Ø stirrups in each support, one 6-Ø stirrup at mid span to keep the grill intact for concreting) strengthened using GFRP fabrics with varying configurations in higher shear zones near both supports. One beam was made weak in shear, strengthened with CFRP fabrics in higher shear zones near both supports. All the beams were simply supported at both ends with 1000mm effective span, 150mm bearings, loaded under more realistic loading conditions, i.e. uniformly distributed loaded (UDL) and tested up to failure by gradually increasing super imposed load. The preparation of concrete surface was done with great care and showed no bond failure in all U-jacketed and inclined stripped beams. One beam bonded with GFRP fabric in the soffit bottom only failed due to debonding. The flexural and shear capacities of the beams are compared with the theoretical prediction using codal provisions. The experimental deflections of beams are also compared with the theoretical predictions. The beams weak in flexure after strengthening showed remarkable flexural strength with 33% to 83% increase in cracking load capacity with respect to the control beam depending on the configuration of GFRP. The four beams weak in shear after strengthening showed 25% to 81% increase in cracking load capacity with respect to the control beam depending on the configuration of GFRP. One beam shear strengthened with CFRP showed remarkable increase of 131% in cracking load capacity and rigidity with respect to the control beam which is highest in the series of tested beams. There was increase in the stiffness of all strengthened beams compared to the control beams.

I. INTRODUCTION

1.1 Fiber Reinforced Polymer (FRP)

Fiber reinforced composite materials consist of fibers of high strength and modulus embedded in or bonded to a matrix with distinct interfaces between them. In this form, both fibers and matrix retain their physical and chemical identities, yet they produce a combination of properties that cannot be achieved with either of the constituents acting alone. Fibers are the principal load carrying members, while the matrix keeps them in the desired location, orientation and protect them from environmental damages. The fiber imparts the strength, while matrix keeps the fiber in place, transfer stresses between the fibers, provides a barrier against an adverse environment such as chemicals and moisture, protects from abrasion. FRP is an acronym for Fiber Reinforced Polymer and identifies a class of composite materials consisting of brittle, high strength and stiffness fibers embedded at high volume fractions in ductile low stiffness and strength polymeric resins called matrix.

FRP with polymeric matrix can be considered as a composite. They are widely used in strengthening of civil structures such as beams, girders, slab, columns and frames. There are many advantages of FRP due to light weight, corrosion-resistant, good mechanical properties. The main function of fibers is to carry load, provide strength, stiffness and stability. The function of the matrix is to keep fibers in position and fix it to the structures. There are mainly three types of fibers dominating the civil engineering industry such as glass, carbon and aramid fibers. Each has its own advantages and disadvantages.

1.2 Methods of forming FRP composites

FRP composites are formed by embedding continuous fibers in resin matrix, which binds the fibers together. The common resins are epoxy resins, polyester resins and vinylester resins, depending on the fibers used. FRP composites are classified into three types:

- Glass-fiber-reinforced polymer (GFRP) composites
- Carbon-fiber-reinforced polymer (CFRP) composites

- Aramid-fiber-reinforced polymer (AFRP) composites

1.3 Advantages and disadvantages of FRP
The various advantages of FRP are:
- Corrosion/wear resistance, lowers maintenance and repair costs.
- High specific strength and stiffness
- Fatigue life.
- Thermal and Acoustical insulation.
- Easier application
- Very high tensile strength, but low weight.
- Repair in limited time without effecting traffic flow/service.

FRP has a great potential for replacing reinforced concrete, and steel reinforcement in bridges, buildings, and other civil infrastructures. Glass fibers are the most common of all reinforcing fibers. Two types of glass fibers commonly used are: (i) E-Glass and (ii) S-Glass.

The disadvantages of FRP are:
- In general compressive strength is lower than the tensile strength.
- Risk of fire and high temperature.
- High cost of carbon fibers.
- Tensile stress-strain diagrams for various reinforcing fibers are almost linear up to the point of failure and have a brittle failure mode.
- Unlike steel reinforcement, it cannot be bent or hooked to provide required anchorage. Poor fire resistance of FRP bars is a serious draw back and hence FRP bars/laminates are not to be proposed for structures where fire is a major design issue.

1.4 Research significance
Numerous old bridges and buildings are in an advanced state of disintegration. The continuing deterioration of the infrastructure highlights the need for effective means of strengthening and rehabilitating of such structures. The strengthening of rectangular RC beams are usually undertaken using fiber reinforced polymer (FRP) fabrics bonded to the beams using epoxy resins. Further, in case of pre-stressed concrete girders in bridges, dummy / service longitudinal cable holes are provided for future strengthening as per need. Similarly, in beams in building dummy longitudinal holes are provided for taking service cables inside and future strengthening as per need. The beams are generally subjected to uniformly distributed loads (UDL) due to self weight and service loads coming over it. Thus, the strengthening of rectangular beams with holes subjected to UDL using FRP is of great technical importance in understanding the flexural and shear behaviour of beams.

II. EXPERIMENTAL PROGRAMME

Experiments are conducted to study the flexural/shear capacity of RC rectangular beams with/without FRP using local available materials.

2.1 Geometry of beams
The geometry of all beams are 1300mm overall length, 1000mm effective length (bearing 150mm each side), 110mm width and 200mm depth with varying reinforcement as per design. The dimensions of all beams are kept same throughout the experiment. Provision of a 30mm diameter service hole is provided along longitudinal direction below the neutral axis in the tension zone of all beams for future strengthening using steel bars, FRP bars or strands in prestressed girders as per practical consideration. All the beams are initially designed as per limit state method of design, simply supported at both ends and applied with multiple concentrated loads equivalent to uniformly distributed load (UDL). All the beams in CB, RB, RF and RS series are gradually test loaded up to failure/collapse.

2.2 Materials
Cement
Portland Slag Cement (PSC) conforming to IS 455 of Konark Brand is used throughout the investigation. It is tested for its physical properties in accordance with Indian Standard specification. The specific gravity of cement was found as 3.10.

Aggregates
The coarse aggregate used in this investigation is crusher broken hard granite chips, maximum size is 20 mm with specific gravity 2.70, grading confirming to IS-383-1970.The fine aggregate used is clean river sand passing through 4.75 sieves with specific gravity of 2.50 and grading zone III confirming to IS-383-1970.

Reinforcing Steel
All longitudinal reinforcement used is HYSD bars confirming to IS 1786: 1979. The stirrups used are 8 mm dia HYSD bars/6 mm dia mild steel bars. The tensile yield strength of HYSD bars used is obtained by testing in the Electronic UTM (FIE make) Model No.UTES 100.

Fibers
Glass and Carbon fibers are used as reinforcing material for FRP. Epoxy is used as the binding material between fiber layers. Glass fibers manufactured by OWEN'S CORNING weighing 360 gms/sqm and Carbon fibers 8H SATIN (T-300) manufactured by TORAY Industries weighing 420 gms/sqm are used for this investigation. Before preparation of specimens test coupons are prepared for characterization of materials used for FRP strengthening. Glass fibers, carbon fibers and epoxy are used for manufacture of test specimens. The test coupons are prepared as per ASTM:D3039M-08 from the FRP plates.

Resin
Polymeric resins are used both as the matrix for the FRP and as the bonding adhesive between the FRP and the concrete. The latter function is of particular concern here, as weak adhesives can cause interfacial failures. Epoxy resins are generally used in the flexural and shear strengthening of beams. The success of the strengthening technique primarily

depends on the performance of the epoxy resin used for bonding of FRP to concrete surface. Numerous types of epoxy resins with a wide range of mechanical properties are commercially available in the market. The epoxy resins are generally available in two parts, a resin and a hardener. The epoxy resin and hardener used in this study are Lapox L-12 and hardener K-6 respectively manufactured by Atual Limited System.

Water
Ordinary clean potable tap water free from suspended particles and chemical substances is used for mixing and curing of concrete throughout the experiment.

III. FORM WORK

Fresh concrete being plastic requires good form work to mould it to the required shape and size. So the form work should be rigid and strong to hold the weight of wet concrete without bulging anywhere. The form work used for concreting all specimens consists of two channels sections having adjustable nuts and bolts, slotted steel plates at the end to fix it to required size as per IS 14687 shown in Fig. 4.1. The joints at bottom and sides are sealed to avoid leakage of cement slurry. Mobil oil was then applied to the inner faces of form work. The bottom rests over thick polythene sheet laid over rigid AS floor. The reinforcement cage is then lowered, placed in position inside the form work carefully with a cover of 20mm on sides and bottom by placing concrete cover blocks. Sample of grill reinforcement used is shown in Fig. 4.2.

Fig.3.1 Typical Steel form

Fig.3.2 Sample of grill reinforcement

Concrete mix proportioning
The design of concrete mix is done as per guidelines of IS 10262: 2009 with a proportion of 1:1.85:3.70 by weight to achieve a grade of M25 concrete. The maximum size of coarse aggregate used is 20 mm. The water cement ratio is fixed at 0.50 and a slump of 50 to 55 mm.

4.1 RESULTS AND DISCUSSION
The experimental results of CB series (control beams) , RF series (weak in flexure) and RS series (weak in shear) beams. Out of 15 beams, 4 are control beams without any FRP strengthening, one beam is made without any steel reinforcement, but strengthened with FRP, 5 beams are made weak in flexure, but strengthened in flexure with FRP and 5 beams are made weak in shear, but strengthened with shear with FRP fabrics in various configurations. All the 15 beams are tested up to failure. Prior to testing of beams, the tensile test results of reinforcing steel as per IS 1786-1985 and test results corresponding to tensile test of FRP laminates as per ASTM: D3039M-08 are presented. The compressive strength of controlled concrete cubes are also presented along with the flexural and shear strength of test beams. Their behavior throughout the test up to failure are described with respect to initial and ultimate load carrying capacity, deflection behaviour, rigidity, ductility, crack pattern and mode of failure.

4.2 Tensile strength of Reinforcing Steel
All the reinforcing steel used are of Shristhi brand and are tested to obtain tensile yield stress in an Electronic UTM Model No. UTES 100 shown in Fig. 5.1, stress-strain curve in Fig. 5.2 and the results in Table 5.1. The average yield strength used in the experiment fy =531 N/ mm^2.

Table 5.1 Tensile test of reinforcing steel

Sl. no of sample	Diameter of bar tested (mm)	0.2% proof stress (yield strength) (N/mm2)	Avg. Yield strength (N/mm2)
1	16	506	
2	16	495	494
3	16	480	
4	12	595	
5	12	560	578
6	12	579	
7	10	530	
8	10	535	529
9	10	521	
10	8	520	
11	8	527	523
12	8	521	

4.3 Determination of Yield stress and Young's modulus of FRP
The yield stress (at 0.2% strain) and Young's Modulus are obtained experimentally by performing unidirectional tensile tests on specimens cut in longitudinal and transverse directions as prescribed in ASTM:D3039M-08 from the FRP

plates fabricated earlier having constant rectangular size 250 mm length × 25mm width. The specimens are cut from the plates by a diamond cutter or by mechanically operated hex saw. After cutting, the sides are polished by sand paper. Three or more sample specimens are prepared from each plate of 2 PLY GFRP, 3 PLY GFRP and 2 PLY CFRP in this experiment, details shown in Table 5.2, 5.3 and 5.4 respectively. The specimens are tested in INSTRON 1195 universal testing machine. Each specimen is fixed in the upper jaw first, and gripped in the movable lower jaw having a gauge length of 150 mm. Gripping of specimen should as much as possible to prevent slippage. The load and extension are recorded digitally with the help of a load cell and an extensometer respectively. The specimen gradually loaded up to failure which is abrupt and sudden as the FRP material is brittle in nature. The INSTRON 1195 machine shown in Fig. 5.3 directly indicated the yield stress, Young's Modulus, ultimate strength and plotted the load-deflection curve shown in Fig. 5.4.The test results of 2 PLY CFRP, 2PLY GFRP and 3 PLY GFRP fabrics are shown in Table 5.5, 5.6 and 5.7 respectively.

Table 5.2 Tensile strength of 2 layer Glass / epoxy laminates

Sample no.	Length of sample (mm)	Width of sample (mm)	Thickness of sample (mm)	Gauge length (mm)	Stress 0.2% Yield(MPa)	Young's Modulus (MPa)
1	250	26	1	150	255.4	20120
2	250	26	1	150	235.3	19470
3	250	26	1	150	232.4	17740
					Mean 241.0	19110

Table 5.3 Tensile strength of 3 layer Glass / epoxy laminates

Sample no.	Length of sample (mm)	Width of sample (mm)	Thickness of sample (mm)	Gauge length (mm)	Stress 0.2% Yield(MPa)	Young's Modulus (MPa)
1	250	24	1.3	150	240.9	19590
2	250	27	1.3	150	277.1	21890
3	250	26	1.3	150	201.7	18820
				Mean	239.9	20100

Table 5.4 Tensile strength of 2 layer Carbon / epoxy laminates

Sample no.	Length of sample (mm)	Width of sample (mm)	Thickness of sample (mm)	Gauge length (mm)	Stress 0.2% Yield(MPa)	Young's Modulus (MPa)
1	255	27.3	0.7	150	476.0	38540
2	255	28.2	0.7	150	571.1	39420
3	255	26.4	0.7	150	642.5	37350
				Mean	563.2	38440

<u>Sample Identification: 2 PLYCFRP</u>

Interface Type: Data Systems Adapter

Machine Parameters of test:

Sample rate (pts/sec): 9.103

Crosshead speed (mm/min): 1.000

Full scale load range (KN): 100.0

Dimensions:	**Spec.1**	**Spec.2**
Width (mm)	27.0	27.0
Thickness (mm)	0.70	0.70
Spec.gauge len (mm)	150.0	150.0
Grip distance (mm)	100.0	100.0

Out of 3Specimens, 0 excluded

Table 5.5 Test Result 2 PLY CFRP

Spec. No.	Displment at Peak(mm)	Strain at Peak(%)	Load at Peak(KN)	Stress at Peak(MPa)	Displment at Break(mm)	Strain at Break(%)	Load at0.2% Yield(KN)	Stress at0.2% Yield(MPa)	Young's Modulus (Mpa)
1	2.767	1.845	11.14	589.7	2.767	1.845	8.996	476.0	38540
2	3.078	2.052	13.04	690.1	3.078	2.052	10.790	571.1	39420
3	2.981	1.987	12.49	661.0	2.981	1.987	12.140	642.5	37350
Mean.	2.942	1.961	12.23	646.9	2.942	1.961	10.640	563.2	38440
Stand. Devtin	0.159	0.106	0.98	51.7	0.159	0.106	1.580	83.6	1041

<u>Sample Identification: 2 PLYGFRP</u>

Interface Type: Data Systems Adapter

Machine Parameters of test:

Sample rate (pts/sec): 9.103

Crosshead speed (mm/min): 1.000

Full scale load range (KN): 100.0

Dimensions:	**Spec.1**	**Spec.2**
Width (mm)	26.0	26.0
Thickness (mm)	1.0	1.0
Spec. Gauge length (mm)	150.0	150.0
Grip distance (mm)	100.0	100.0

Out of 3Specimens, 0 excluded

Humidity (%): 50

Table 5.6 Test Result 2 PLY GFRP

Temp (deg,F): 73

Spec. No.	Displment at Peak(mm)	Strain at Peak(%)	Load at Peak(KN)	Stress at Peak(MPa)	Displment at Break(mm)	Strain at Break (%)	Load at0.2% Yield(KN)	Stress at0.2% Yield(MPa)	Young's Modulus (Mpa)
1	5.163	3.442	13.34	513.0	5.165	3.443	6.642	255.4	20120
2	4.599	3.066	11.89	457.3	4.599	3.066	6.117	235.3	19470
3	4.805	3.203	11.49	441.9	4.805	3.203	6.042	232.4	17740
Mean.	4.855	3.237	12.24	470.7	4.856	3.237	6.267	241.0	19110
Stand. Devtin	0.285	0.19	0.97	37.4	0.287	0.191	0.327	12.6	1231

Sample Identification: 3 PLY GFRP

Interface Type: Data Systems Adapter

Machine Parameters of test:

Sample rate (pts/sec): 9.103

Crosshead speed (mm/min): 1.000

Full scale load range (KN): 100.0

Dimensions:	**Spec.1**	**Spec.2**	
Width (mm)	26.0	26.0	26.0
Thickness (mm)	1.3	1.3	1.3
Spec.gauge length (mm)	150.0	150.0	150.0
Grip distance (mm)	100.0	100.0	100.0

Out of 3Specimens, 0 excluded

Table 5.7 Test Result 3 PLY GFRP

Spec. No.	Displment at Peak(mm)	Strain at Peak(%)	Load at Peak(KN)	Stress at Peak(MPa)	Displment at Break(mm)	Strain at Break (%)	Load at0.2% Yield(KN)	Stress at0.2% Yield(MPa)	Young's Modulus (Mpa)
1	5.119	3.413	17.24	510.0	5.119	3.413	8.141	240.9	19590
2	5.494	3.663	20.13	595.7	5.494	3.663	9.365	277.1	21890
3	3.500	2.333	11.09	328.1	5.607	3.738	6.817	201.7	18820
Mean.	4.704	3.136	16.15	477.9	5.407	3.604	8.108	239.9	20100
Stand. Devtin	1.060	0.707	4.620	136.7	0.256	0.170	1.275	37.7	1597

Table 5.8 Compressive strength of test cubes for CB series

Cube sample	Weight of cubes (Kg)	Cube strength after 7 days (N/mm^2)	7 days avg. Cube strength (N/mm^2)	Cube strength after 28 days (N/mm^2)	28 days avg. Cube strength (N/mm^2)
1	8.396	20.89		-	
2	8.242	18.67		-	
3	8.300	19.56	19.71	-	29.65
4	8.280	-		29.65	
5	8.342	-		31.39	
6	8.288	-		27.9	

Table 5.9 Compressive strength of test cubes for RF series

Cube sample	Weight of cubes (Kg)	Cube strength after 7 days (N/mm^2)	7 days avg. Cube strength (N/mm^2)	Cube strength after 28 days (N/mm^2)	28 days avg. Cube strength (N/mm^2)
1	8.235	20.49		-	
2	8.278	20.36		-	
3	8.295	20.53	20.46	-	30.33
4	8.204	-		29.87	
5	8.316	-		30.35	
6	8.268	-		30.78	

Table 5.10 Compressive strength of test cubes for RS series

Cube sample	Weight of cubes (Kg)	Cube strength after 7 days (N/mm^2)	7 days avg. Cube strength (N/mm^2)	Cube strength after 28 days (N/mm^2)	28 days avg. Cube strength (N/mm^2)
1	8.270	20.27		-	
2	8.305	20.45		-	
3	8.295	20.14	20.29	-	30.44
4	8.283	-		29.93	
5	8.295	-		30.39	
6	8.278	-		31.02	

5.5 Load prediction

The analysis of predicted load is made as per L.S.M (IS method) and U.L.M (Whitney's theory) for control beams, British code BS 8110-1997 for flexurally strengthened beams and ACI format ACI 318-95-1991 for shear strengthened beams. The predicted loads are calculated as follows.

5.5.1 Flexural capacity of beam by Limit State Method (IS456-2000)

Beam CB1 The cross section of the beam CB1 is shown in Fig.5.7

Fig. 5.7 Cross section CB1

Clear cover = 20mm, f_{ck} = 30 N/mm^2, f_y = 531 N/mm^2, A_{st}= 12Φ-2nos =226.28mm^2, d=174mm

It is a balanced section (slightly under reinforced), so MR is governed by steel area $M_{lim} = 0.822 f_y A_{st} d$

= 0.822×531×226.28×174

= 17.19 KNm

Bending Moment (BM) = $0.125w\ell^2$ = 17.19 KNm
So load, w = 138 KN

Beam CB2 The cross section of the beam CB2 is shown in Fig.5.8

Fig.5.8 Cross section CB2

Under reinforced section, weak in flexure, but strong in shear.
Clear cover = 20mm, f_{ck} = 30 N/mm^2, f_y = 531 N/mm^2, A_{st}= 10Φ-2nos =157.14mm^2, d=175mm
It is a highly under reinforced section, so MR is governed by steel area.

M_{lim} = $0.822 f_y A_{st}$ d
= 0.822×531×157.14×175
= 12.0 KNm

Bending Moment (BM) = $0.125w\ell^2$ = 12.0 KNm
So load, w = 96 KN

Beam CB3 The cross section of the beam CB3 is shown in Fig.5.9

Fig. 5.9 Cross section CB3

Over reinforced section, weak in shear
Clear cover = 20mm, f_{ck} = 30 N/mm^2, f_y = 531 N/mm^2
A_{st}= 16Φ-2nos = 402.28mm^2, d = 172mm, b = 110mm, S_v = 8Φ @ 300 c/c
It is a highly over reinforced section, so MR is governed by shear only
τ_c=
$V_u = V_{uc} + V_{us}$
Vuc = τcmax × b d
$\tau_{cmax} = 0.8\sqrt{f_{ck}} = 0.8\sqrt{30}$ = 4.382N/mm^2 as per BS 8110-1985
$V_{uc} = \tau_{cmax}$ × b d = 4.382×110×172 = 82.91 KN
V_{us} = = 531×100.56×172/300 = 30.62 KN
V_u = 113.53 KN
So the initial cracking load = 2×113.53 = 227 KN

Beam CB4 The cross section of the beam CB4 is shown in Fig.5.10

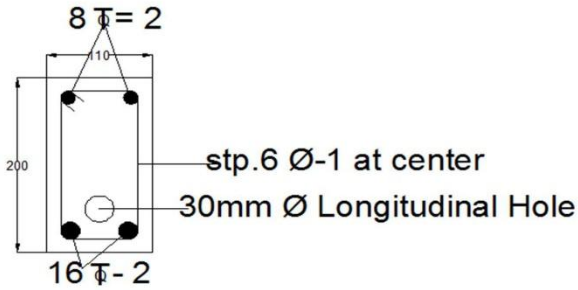


Fig. 5.10 Cross section CB4

Over reinforced section in flexure, very weak in shear. In fact no shear reinforcement is provided
Clear cover = 20mm, f_{ck} = 30 N/mm^2, f_y = 531 N/mm^2
A_{st}= 16Φ-2nos = 402.28mm^2, d = 172mm, b = 110mm
It is a highly over reinforced section, so MR is governed by shear only
τ_c =
$V_u = V_{uc} + V_{us}$
Vuc = τcmax × b d
$\tau_{cmax} = 0.8\sqrt{f_{ck}} = 0.8\sqrt{30}$ = 4.382N/mm^2 [as per BS 8110-1985]
$V_{uc} = \tau_{cmax}$ × b d = 4.382×110×172 = 82.91 KN
V_{us} = = 0 since no shear reinforcement is provided
V_u = 82.91 KN
So the initial cracking load = 2×82.91 = 166 KN

5.5.2 Flexural capacity of beam by Ultimate Load Method (Whitney's Theory)

Beam CB1
Clear cover = 20mm, f_{ck} = 30 N/mm^2, f_y = 531 N/mm^2, A_{st}= 12Φ-2nos =226.28mm^2
d=174mm, b= 110mm
So, the mode of failure is primary tension failure. Ultimate MR is governed by steel area.
$M_u = T_u$× Lever arm = $A_{st} f_y$ (d-) = 17.63 KNm
$W\ell^2/8$ = 17.63
Initial cracking load, w = 141 KN

Beam CB2

Clear cover = 20mm, f_{ck} = 30 N/mm^2, f_y = 531 N/mm^2, A_{st}= 10Φ-2nos =157.14mm^2
d=175mm, b= 110mm

So, the mode of failure is primary tension failure. Ultimate MR is gove
Mu = T_u× Lever arm = $A_{st} f_y$ (d-) = 13.02 KNm
$w\ell^2/8$ = 13.02
Initial cracking load , w = 104KN

Beam CB3

The beam is weak in shear.
Clear cover = 20mm, f_{ck} = 30 N/mm^2, f_y = 531 N/mm^2
A_{st}= 16Φ-2nos = 402.28mm^2, d = 172mm, b = 110mm,
Stirrups S_v = 8Φ-2leg.stp.@ 300 c/c

It is a highly over reinforced section, MR is governed by shear only

τ_c=

$V_u = V_{uc} + V_{us}$

Vuc = τcmax × b d

τcmax = 0.8√fck = 0.8√30 = 4.382N/mm^2 as per BS 8110-1985

$V_{uc} = \tau_{cmax} \times b\, d = 4.382\times110\times172 = 82.91$ KN

Beam CB4

Very weak in shear. In fact no shear reinforcement is provided

Clear cover = 20mm, f_{ck} = 30 N/mm^2, f_y = 531 N/mm^2

A_{st}= 16Φ-2nos = 402.28mm^2, d = 172mm, b = 110mm

MR is governed by shear only

τ_c =

Vu = Vuc + Vus

Vuc = τcmax × b d

$\tau_{cmax} = 0.8\sqrt{f_{ck}} = = 0.8\sqrt{30} = 4.382$N/mm^2

[as per BS 8110-1985]

$V_{uc} = \tau_{cmax} \times b\, d = 4.382\times110\times172 = 82.91$ KN

V_{us} = = 0

since no shear reinforcement is provided

V_u = 82.91 KN

So the initial cracking load = 2×82.91 = 166 KN

5.2.3 Shear strength of FRP strengthened beams (RS1 to RS5)

Beam RS1 The cross section of the beam RS1 is shown in Fig.5.11

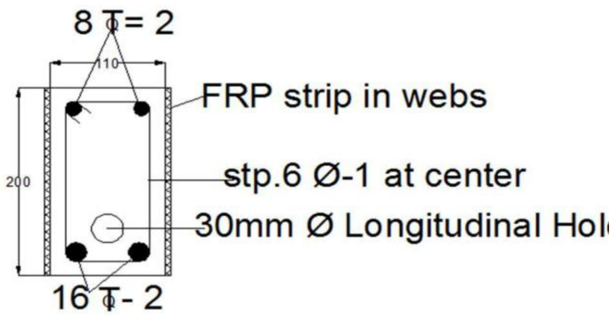


Fig. 5.11 Cross section RS1

Strengthened with 2 layers of GFRP in webs near supports for a length of 300mm

Vs = 0

Vfrp = Φfrp Afrp

ffrp ( ) d

Φ_{frp} = 0.80, d = effective depth of beam = 164mm

Afrp = tfrp× wfrp, t_{frp} = thickness of FRP = 0.70 mm, w_{frp} = width of FRP = 300mm

= 2 sides × 0.70 × 300 = 420 mm^2

$S_{frp} = w_{frp}$ = 300mm

f_{frp} = 563.2 N/mm^2, Angle β = (oriented 90^0 to the horizontal) = 90^0

$$V_{frp} = \frac{0.80\times420\times563.2}{300}\times164 = 103.45 \text{ KN}$$

V_n = 79+0+103.45=182.45 KN

Initial cracking load=2×182.45=364.9, say 365 KN

5.5.4 Flexural strength of FRP strengthened beams (RF1 to RF5) (BS 8110- 1997)

Beam RF1 The cross section of the beam RF1 is shown in Fig.5.16

The factor of safety $_{frp}$, $_s$, $_c$ are taken as unity as ultimate load of the FRP strengthened beam is required here.

Fig. 5.16 Cross section RF1

The depth of neutral axis x can be determined by solving the following force equilibrium equation.

k1 b x + si Asi + frp Afrp = 0

f_{cu} = 30N /mm^2, $_c$ = 1,

∈ = = = 1.336×10^{-3}

Assuming crushing of concrete, limiting value of ∈ = 0.003

$$K_1 = 0.67\left(1-\frac{\in}{\in}\right) = 0.585$$

$$K_2 = \frac{\in / \quad \in \quad /(\quad \in\ ) \in /}{\in \quad \in \quad /} = 0.441$$

$_{si}$ = 531 N/mm^2, A_{si} = 2-10Φ = 157.14mm^2, $A_{frp} = t_{frp} \times b_{frp}$ = 100mm^2

Mean value of $_{frp}$ from testing = 241 N/mm^2, d_{si} = 175mm

Putting all above values in the equation given below

k_1 b x + ∑ $^\sigma$si Asi + frp Afrp = 0

x = -56.96mm

Moment of resistance
$M_u = k_1$ b x (- k_2x) + ∑ σ_{si} A_{si} (- d_{si}) +
Substituting all the values in the above equation, M_u = -22.667 KNm
Moment of resistance wℓ^2/8 = 22.667, neglecting – sign
Initial cracking load w = 181 KN as factor of safety is taken as unity for all material strength.
The above derivative also applies to **RF2 / RF4 / RF5**, Where MR = 22.667 and cracking load w = 181 KN

Beam RF3 The cross section of the beam RF3 is shown in Fig.5.17

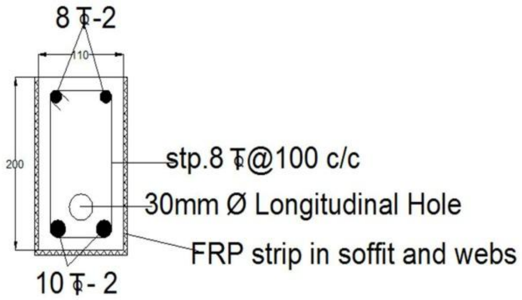


Fig. 5.17 Cross section RF3

The depth of neutral axis x can be determined by solving the following force equilibrium equation.

k_1 b x + ∑ σ_{si} Asi + frp Afrp = 0

As per above

K_1 = 0.585, f_{ck} = 30 N/mm^2, $_c$ = 1, b= 110mm, $_{si}$ = 531 N/mm^2 a K_2 = 0.441
A_{si} = 2-10Φ = 157.14mm^2, $A_{frp} = t_{frp} \times b_{frp}$ = 1.3×110mm^2 = 143mm^2
Mean value of frp from testing = 239.9 N/mm^2, d_{si} = 175mm
Putting these values in the above equation
x = -61mm
Moment of resistance
$M_u = k_1$ b x (- k_2x) + $_{si}$ A_{si} (- d_{si}) + $_{frp}$ A_{frp} (− d_{frp})
Substituting all the appropriates values in the above equation, M_u = -24.633 KNm

Moment of resistance wℓ^2/8 = 24.633, neglecting –ve sign
Initial cracking load w = 197 KN as factor of safety is taken as unity for all material strength.

Beam RB1

No reinforcement is provided.1000mm length 2 layers of GFRP U-wrapped for the full span.

k1 b x + si Asi + frp Afrp = 0

As before f_{cu} = 30 N/mm^2, $_c$ = 1, K_1 = 0.585, A_{si} = 0, σ =531 N/r
Mean value of $_{frp}$ from testing = 241 N/mm^2, $A_{frp} = t_{frp} \times b_{frp}$ = 110m
Substituting all the appropriates values in the above equation, x = -13.732mm
$_{frp}$ A_{frp} (− d_{frp})
Moment of resistance

$M_u = k_1$ b x (- k_2x) + ∑ si Asi (- d_{si}) +
Substituting all the appropriates values in the above equation, M_u = -5.46
Moment of resistance, wℓ^2/8 = 5.462, neglecting –ve sign
Initial cracking load w = 44 KN, factor of safety is taken as unity f

5.6 Testing of beams, crack pattern and failure mode

All the 15 beams are tested one by one in the loading frame. Three dial gauges are fixed below the beam each one at quarter span, mid span and three-fourth span. The load is gradually increased up to failure. The deflections are recorded up to initial cracking load. After the needles in the dial gauge rotated rapidly indicating approach of imminent failure, the dial gauges are removed to save from damage during failure of beams.

Beam CB1

The geometry and reinforcement in the beam is shown in Fig.5.18. The beam is provided with balanced (slightly under reinforced) reinforcement. It is gradually loaded up to failure. The loading of beam, crack pattern with failure mode and load-deflection curve is shown in Fig. 5.19,

5.20 and 5.21 respectively given below. Hair cracks are appeared at mid span bottom, progressed upwards, gradually cracks widened, yielding of steel seen, then crushing of concrete at mid span top and failure occurred. It is a pure flexural failure. The theoretical cracking load as per LSM and ULM of design is 138 KN and 141 KN respectively. The experimental results showed an initial cracking load of 210 KN and ultimate load of 292KN shown in Table 5. 11.

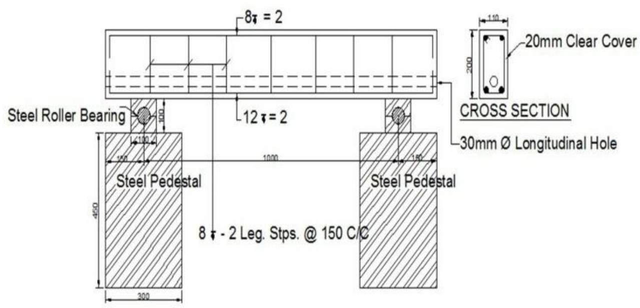


Fig. 5.18 Longitudinal section beam CB1

Fig 5.19 Loading arrangement beam CB1

Fig. 5.20 Failure of beam CB1

Table 5.11 EXPERIMENTAL RESULT OF CONTROL BEAMS

Beam specimen	Type of beam	Reinforcement provided – Tor steel			Initial Cracking/ Ultimate Load (KN)				Deflection (mm)			Deflection Load KN
		Top	Bottom	Shear	Limit state method	Ultimate load method	Experimental result		1/4 span	Mid span	3/4 span	
							Cracking load	Ultimate load				
CB1	Balanced	8 ϕ -2	12 ϕ -2	8 ϕ @ 150 C/C	138	141	210	292	0.97	1.15	1.00	110
CB2	Weak in flexure but strong in shear	8 ϕ -2	10 ϕ -2	8 ϕ @ 100 C/C	96	104	120	170	1.35	2.48	1.35	110
CB3	Weak in shear but strong in flexure	8 ϕ -2	16 ϕ -2	8 ϕ @ 300 C/C	227	227	290	367	3.1	3.35	2.82	340
CB4	Weak in shear but strong in flexure	8 ϕ -2	16 ϕ -2	6 ϕ – 5 nos	166	166	160	360	2.36	2.45	2.15	260

Control beam CB2

The geometry and reinforcement in the beam is shown in fig.5.22. The reinforcement is provided so as to make the beam weak in flexure but strong in shear. The beam is made weak in flexure, but strong in shear by providing suitable reinforcement. It is gradually loaded up to failure. The crack pattern, mode of failure and load-deflection curve is shown in the Fig. 5.23, 5.24 and 5.25 respectively. Small hair cracks appeared at mid span bottom, progressed upwards, crack widened, yielding of tensile steel were seen, followed by crushing of concrete at mid span top. It is purely a flexural failure. The theoretical cracking load as per LSM and ULM of design was 96 KN and 104 KN respectively. The experimental results showed an initial cracking load 120 KN and ultimate load of 170KN as shown in the Table 5.11.

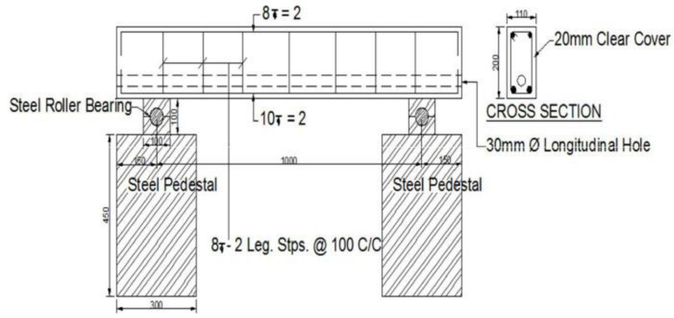
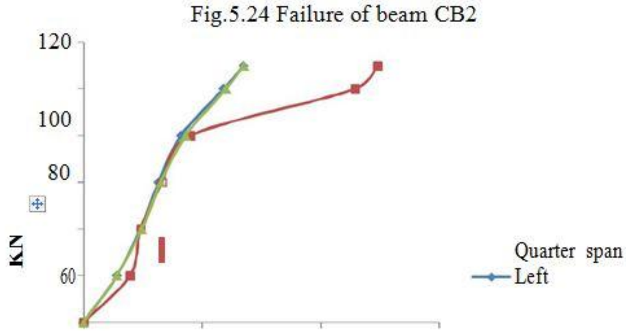


Fig**.** 5.22 Longitudinal section beam CB2

Fig.5.23 Crack pattern beam CB2

Fig.5.24 Failure of beam CB2



Control beam CB3

The geometry and reinforcement in the control beam CB3 is shown in fig.5.26. The reinforcement is provided so as to make the beam weak in shear but strong in flexure. It is gradually loaded up to failure. The mode of failure and load-deflection curve is shown in the Fig. 5.27 and 5.28 respectively. Inclined hair cracks appeared near one support from bottom, then crack appeared in the other support, cracks progressed upwards and widened gradually, went up to top of beam followed by crushing of concrete along the crack line and top, where the shear crack meets the beam top. It is a pure shear failure. The theoretical cracking load as per LSM of design is 227 KN. The experimental results showed an initial cracking load of 290 KN and ultimate load of 367 KN shown in the Table 5. 11.

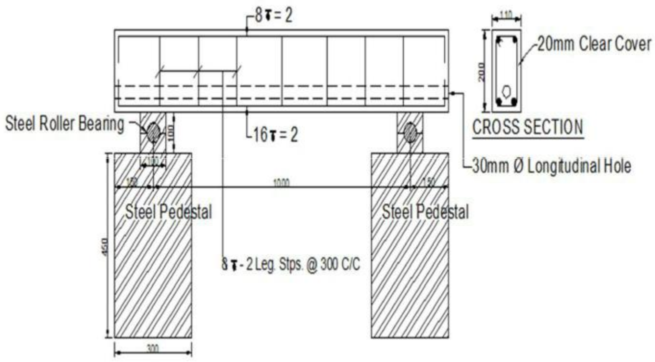


Fig.5.26 Longitudinal section beam CB3

Fig.5.27 Failure of beam CB3

6. CONCLUSION

6.1 Introduction

This chapter presents the conclusion of experimental study on the flexural/shear capacity of RC rectangular beams with/without FRP.

6.2 Shear Strengthening

To study the performance of RC beam in shear, five beams were made weak in shear, strengthened in shear with bonded GFRP and CFRP strips. Following are the observations noted.

The shear strength of FRP strengthened beams at the stage of initial cracking is noted as below.

Beam Designation	Load (w) kN
Beam RS1	284
Beam RS2	284
Beam RS3	323
Beam RS4	285
Beam RS5	365

6.3 Flexural Strengthening

To study the performance of RC beam in flexure, five beams were made weak in flexure, strengthened in flexure with bonded GFRP strips. Following are the observations noted.

The load carrying capacity of the beams at the stage of initial cracking designed using Limit State Method is noted as below.

Beam Designation	Load (w) kN
Beam CB1	138
Beam CB2	96
Beam CB3	227
Beam CB4	166

The load carrying capacity of the beams at the stage of initial cracking designed using Ultimate Load Method (Whitney's Theory) is noted as below.

Beam Designation	Load (w) kN
Beam CB1	141
Beam CB2	104
Beam CB3	227
Beam CB4	166

The flexural strength of FRP strengthened beams at the stage of initial cracking is noted as below.

Beam Designation	Load (w) kN
Beam RF1	181
Beam RF2	181
Beam RF3	197
Beam RF4	181
Beam RF5	181

- Compressive strength of RS series cubes is slightly greater than RF and CB series for both 7 and 28 days testing.
- Beam CB3 which is weak in shear but strong in flexure has shown better performance than all other beams.

Beam CB3 and CB4 designed using LSM and ULM has shown the same results.

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