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
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.

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 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

<table>
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<tr>
<th>Sl. no of sample</th>
<th>Diameter of bar tested (mm)</th>
<th>0.2% proof stress (yield strength) (N/mm$^2$)</th>
<th>Avg. Yield strength (N/mm2)</th>
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</table>

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.

![Fig.3.1 Typical Steel form](image1)

![Fig.3.2 Sample of grill reinforcement](image2)
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.

### Sample Identification: 2 PLY CFRP

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:

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<th>Spec.2</th>
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<td>Spec.gauge len (mm)</td>
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<td>Grip distance (mm)</td>
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Out of 3Specimens, 0 excluded

### Table 5.5 Test Result 2 PLY CFRP

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<tr>
<th>Sample no.</th>
<th>Displacement at Peak(mm)</th>
<th>Strain at Peak(%)</th>
<th>Load at Peak(KN)</th>
<th>Stress at Break(MPa)</th>
<th>Elongation at Break(mm)</th>
<th>Stress at 0.2% Yld(MPa)</th>
<th>Young’s Modulus(MPa)</th>
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<td>662.5</td>
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Mean:
- Load: 2.992 ± 1.961
- Stress at 0.2% Yld: 646.9 ± 2.042
- Young’s Modulus: 562.2 ± 18440

**Sample Identification: 2 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:

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<td>Grip distance (mm)</td>
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Out of 3Specimens, 0 excluded

### Table 5.6 Test Result 2 PLY GFRP

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<th>Sample no.</th>
<th>Displacement at Peak(mm)</th>
<th>Strain at Peak(%)</th>
<th>Load at Peak(KN)</th>
<th>Stress at Break(MPa)</th>
<th>Elongation at Break(mm)</th>
<th>Stress at 0.2% Yld(MPa)</th>
<th>Young’s Modulus(MPa)</th>
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<td>662.5</td>
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</table>

Mean:
- Load: 2.992 ± 1.961
- Stress at 0.2% Yld: 646.9 ± 2.042
- Young’s Modulus: 562.2 ± 18440

**Sample Identification: 2 PLY GFRP**
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:

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<th>Spec.</th>
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Out of 3 Specimens, 0 excluded

Table 5.7 Test Result 3 PLY GFRP

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Table 5.8 Compressive strength of test cubes for CB series

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<th>Cube sample</th>
<th>Weight of cubes (Kg)</th>
<th>Cube strength after 7 days (N/mm²)</th>
<th>7 days avg. Cube strength (N/mm²)</th>
<th>Cube strength after 28 days (N/mm²)</th>
<th>28 days avg. Cube strength (N/mm²)</th>
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Table 5.9 Compressive strength of test cubes for RF series

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<th>7 days avg. Cube strength (N/mm²)</th>
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Table 5.10 Compressive strength of test cubes for RS series

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<td>3</td>
<td>8.295</td>
<td>20.14</td>
<td>20.29</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>8.283</td>
<td>-</td>
<td>20.83</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>8.295</td>
<td>-</td>
<td>30.19</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>8.270</td>
<td>-</td>
<td>31.02</td>
<td>-</td>
<td></td>
</tr>
</tbody>
</table>

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, $f'_c = 30$ N/mm², $f_y = 531$ N/mm², $A_{st} = 1.204$, $2n = 226.28$mm², $d = 174$mm
It is a balanced section (slightly under reinforced), so MR is governed by steel area $M_{lim} = 0.822f_y A_{st} d = 0.822\times531\times226.28\times174 = 17.19$ KNm
Bending Moment (BM) = \(0.125wℓ^2 = 17.19\text{ KNm}\)
So load, \(w = 138\text{ KN}\)

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

![Fig. 5.8 Cross section CB2](image)

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

\[
M_{lim} = 0.822 f_y A_e d = 0.822 \times 531 \times 157.14 \times 175 = 12.0\text{ KNm}
\]

Bending Moment (BM) = \(0.125wℓ^2 = 12.0\text{ KNm}\)
So load, \(w = 96\text{ KN}\)

**Beam CB3**  
The beam is weak in shear.
Clear cover = 20mm, \(f_{ck} = 30\text{ N/mm}^2, f_y = 531\text{ N/mm}^2\), \(A_e = 16\Phi-2\text{nos} = 402.28\text{mm}^2, d = 172\text{mm}, b = 110\text{mm}\)
It is a highly over reinforced section, so MR is governed by shear only

\[
\tau_c = \frac{V_u}{V_{uc} + V_{us}}
\]

\[
V_u = V_{uc} + V_{us}
\]

\[
V_{uc} = \tau_{cmax} \times b \times d
\]

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

\[
V_{uc} = \tau_{cmax} \times b \times d = 4.382 \times 110 \times 172 = 82.91\text{ KN}
\]

\[
V_{us} = 0
\]

\[
V_u = 82.91\text{ KN}
\]
So the initial cracking load = \(2 \times 82.91 = 166\text{ KN}\)

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

**Beam CB1**  
Clear cover = 20mm, \(f_{ck} = 30\text{ N/mm}^2, f_y = 531\text{ N/mm}^2, A_e = 12\Phi-2\text{nos} = 226.28\text{mm}^2\)
\(d = 174\text{mm}, b = 110\text{mm}\)
So, the mode of failure is primary tension failure. Ultimate MR is governed by steel area.

\[
M_u = T_u \times \text{Lever arm} = A_e f_y (d - ) = 17.69\text{ KNm}
\]

\[
Wu/8 = 17.63
\]
Initial cracking load, \(w = 141\text{ KN}\)

**Beam CB2**  
Clear cover = 20mm, \(f_{ck} = 30\text{ N/mm}^2, f_y = 531\text{ N/mm}^2, A_e = 10\Phi-2\text{nos} = 157.14\text{mm}^2\)
\(d = 175\text{mm}, b = 110\text{mm}\)
So, the mode of failure is primary tension failure. Ultimate MR is governed by steel area.

\[
M_u = T_u \times \text{Lever arm} = A_e f_y (d - ) = 13.02\text{ KNm}
\]

\[
wu/8 = 13.02
\]
Initial cracking load, \(w = 104\text{ KN}\)

**Beam CB3**  
The beam is weak in shear.
Clear cover = 20mm, \(f_{ck} = 30\text{ N/mm}^2, f_y = 531\text{ N/mm}^2, A_e = 16\Phi-2\text{nos} = 402.28\text{mm}^2, d = 172\text{mm}, b = 110\text{mm}\)
Stirrups \(S_v = 8\Phi-2\text{leg.stp.}@ 300\text{ c/c}\)
It is a highly over reinforced section, MR is governed by shear only
\[
\tau_c = \frac{V_u}{b_d} = \frac{V_{uc} + V_{us}}{b_d} = \tau_{cmax} \times b_d
\]
\[
\tau_{cmax} = 0.8\sqrt{f_{ck}} = 0.8\times\sqrt{30} = 4.382 \text{N/mm}^2 \quad \text{as per BS 8110-1985}
\]
\[
V_{uc} = \tau_{cmax} \times b_d = 4.382 \times 110 \times 172 = 82.91 \text{ KN}
\]
\[
V_{us} = 0 \quad \text{since no shear reinforcement is provided}
\]
\[
V_u = 82.91 \text{ KN}
\]
So the initial cracking load = 2\times82.91 = 166 \text{ 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

\[
\Phi_{frp} = 0.80, \quad d = \text{effective depth of beam} = 164 \text{mm}
\]
\[
V_{frp} = \Phi_{frp} A_{frp}
\]
\[
f_{frp} = 563.2 \text{ N/mm}^2, \quad \beta = (\text{oriented 90}^\circ \text{ to the horizontal}) = 90^\circ
\]
\[
V_{frp} = 0.80 \times 420 \times 563.2 \times 164 = 103.45 \text{ KN}
\]
\[
V_n = 79+0+103.45 = 182.45 \text{ KN}
\]
Initial cracking load = 2\times182.45 = 364.9, say 365 \text{ 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 \( s_c \) are taken as unity as ultimate load of the FRP strengthened beam is required here.

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

\[
k_1 b x + \sum A_i f_{ci} + \Phi_{frp} A_{frp} = 0
\]
\[
f_{cu} = 30 \text{N/mm}^2, \quad \epsilon = 1,
\]
\[
\epsilon = 1.336\times10^{-3}
\]
Assuming crushing of concrete, limiting value of \( \epsilon \) = 0.03

\[
k_1 = 0.67 (1- \frac{\epsilon}{\epsilon_c}) = 0.585
\]
\[
k_2 = \frac{\epsilon / \epsilon_c}{(1- \epsilon / \epsilon_c)} = 0.441
\]
\[
\sum A_i = 2-10\Phi = 157.14 \text{mm}^2, \quad A_{frp} = t_{frp} \times b_{frp} = 100 \text{mm}^2
\]
\[
s_i = 531 \text{ N/mm}^2, \quad \Phi_{frp} = \Phi_{frp} A_{frp}
\]
Moment of resistance $Wt^2/8 = 24.633$, neglecting the 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.

$$k_1 b x + \sum \sigma_i A_i + \text{frp Afrp} = 0$$

As before $f_{ck} = 30$ N/mm$^2$, $c = 1$, $K_i = 0.585$, $A_{si} = 0$, $\sigma_c = 531$ N/mm$^2$

Mean value of $frp$ from testing = 241 N/mm$^2$, $A_{frp} = t_{frp} \times b_{frp} = 110mm$.

Substituting all the appropriate values in the above equation, $M_a = -22.667$ KNm

Moment of resistance $wℓ = 24.667$, neglecting the sign

Initial cracking load $w = 181$ KN as factor of safety is taken as unity for all material strength.

**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, 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 292 KN shown in Table 5.11.
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 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. 5.23, 5.24 and 5.25 respectively. Inclined hair cracks appeared near one support from bottom, then 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 experimental results showed an initial cracking load 120 KN and ultimate load of 170KN as shown in the Table 5.11.

**Table 5.11 EXPERIMENTAL RESULT OF CONTROL BEAMS**

<table>
<thead>
<tr>
<th>Beam</th>
<th>Type of beam</th>
<th>Reinforcement provided</th>
<th>Fracture Load (kN)</th>
<th>Deflection (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CB1</td>
<td>Balanced</td>
<td>13 8 - 2</td>
<td>134</td>
<td>1.47 1.47 1.00</td>
</tr>
<tr>
<td>CB2</td>
<td>Weak in flexure but strong in shear</td>
<td>13 8 - 2</td>
<td>134</td>
<td>1.47 1.47 1.00</td>
</tr>
<tr>
<td>CB3</td>
<td>Weak in shear but strong in Beam</td>
<td>13 8 - 2</td>
<td>134</td>
<td>1.47 1.47 1.00</td>
</tr>
<tr>
<td>CB4</td>
<td>Weak in shear but strong in Steel</td>
<td>13 8 - 2</td>
<td>134</td>
<td>1.47 1.47 1.00</td>
</tr>
</tbody>
</table>

**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.
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.

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.

<table>
<thead>
<tr>
<th>Beam Designation</th>
<th>Load (w) kN</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam RS1</td>
<td>284</td>
</tr>
<tr>
<td>Beam RS2</td>
<td>284</td>
</tr>
<tr>
<td>Beam RS3</td>
<td>323</td>
</tr>
<tr>
<td>Beam RS4</td>
<td>285</td>
</tr>
<tr>
<td>Beam RS5</td>
<td>365</td>
</tr>
</tbody>
</table>

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.

<table>
<thead>
<tr>
<th>Beam Designation</th>
<th>Load (w) kN</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam CB1</td>
<td>138</td>
</tr>
<tr>
<td>Beam CB2</td>
<td>96</td>
</tr>
<tr>
<td>Beam CB3</td>
<td>227</td>
</tr>
<tr>
<td>Beam CB4</td>
<td>166</td>
</tr>
</tbody>
</table>

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

<table>
<thead>
<tr>
<th>Beam Designation</th>
<th>Load (w) kN</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam RF1</td>
<td>181</td>
</tr>
<tr>
<td>Beam RF2</td>
<td>181</td>
</tr>
<tr>
<td>Beam RF3</td>
<td>197</td>
</tr>
<tr>
<td>Beam RF4</td>
<td>181</td>
</tr>
<tr>
<td>Beam RF5</td>
<td>181</td>
</tr>
</tbody>
</table>

- 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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