Comparative Study on Flexural Strengthening of RC Beams using CFRP Laminate by Different Techniques

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Abstract: This paper presents a detailed study on flexural behaviour of RC beams strengthened using Carbon Fiber Reinforced Polymer (CFRP) laminate. A detailed study was made on strengthened beam using Externally Bonded Laminate (EBL) and Internally Bonded Laminate (IBL) techniques. In IBL technique the laminate is sandwiched between the layers of epoxy mounted on the cover portion by the groove. The beams were designed as under-reinforced section. Totally six beams were casted, out of this two beams were control beams. Strengthened beams were divided into two sets (IBL and EBL) of two beams each. The main aim of this work is to delay the debonding failure in order to enhance the ultimate load carrying capacity for strengthened beams. Four-point bending flexural tests were conducted on specimens up to failure. The experimental results illustrate that, the strengthened beams significantly increases the cracking, working and ultimate load when compared with control beams. IBL technique shows the significant increase in the debonding strain by delaying the beam from debonding failure which in turn enhances the ultimate load by almost 73% compared with control beam and 39% with EBL technique. All the deflection values from the experiments are within the limit of codal provisions. The IBL technique was emerged as the better strengthening technique, which increases almost 41% of working load (Pw) compared with strengthening codes.

Keywords: Carbon Fiber Reinforced Polymer (CFRP), Debonding, Externally Bonded Laminate (EBL), Flexural behaviour, Internally Bonded Laminate (IBL), Laminate, RC Beams.

1. INTRODUCTION
The strengthening of existing RC structures is most important in order to satisfy the requirements such as increasing the load carrying capacity, life, durability and reliability of the structures. The strengthening technique for the existing or damaged structures are implemented by surface treatments, external post tensioning, external reinforcement and jacketing using steel plates or ferrocement etc., is the common method followed in construction industry. This method can be effectively replaced by application of Fiber Reinforced Polymer (FRP) composites. Since lot of research has been done for past years on strengthening of RC structures using FRP and these research experiences have been used in several practical cases with new technical knowledge and confidence. The research work carried out by various researchers around the world in the area of strengthening of RCC member by various CFRP techniques. On this basis the research work will be carried out, which is of utmost interest depending upon the relative field and this acts as motivation for further research work. In this work the main aim is
to improve the load carrying capacity of the beams by satisfying the serviceability requirement. The main study had been done on the bond characteristics between CFRP and concrete to maintain the proper bonding [1]-[3]. The debonding strain in the laminate is most critical according to the failure of the beam is concerned, since most of the strengthened beams fails due to premature debonding, not achieving the required rupture strain as per the specification of laminate. Hence the study has been done on the debonding strain [4], [5]. In the past research the attempt has been made to delay the debonding failure by different techniques [6]-[10].

2. MATERIALS AND PROPERTIES

2.1 Concrete and Steel reinforcement
In the present research work, the mix design for concrete was carried out according to IS: 10262-2009. The compressive strength of concrete used in this experimental work was 40 N/mm². The steel reinforcements used are HYSD (High yield strength deformed) bars having tensile strength of 500N/mm².

2.2 Strengthening Material:-
The methodology of application of external reinforcement on the beams increases its load carrying capacity by generating a higher internal couple of transversal section but leaving the weight of the structural element practically same. The CFRP composites with adorable properties and advantages such as high stiffness, tensile strength, durability, corrosion resistant, electro-magnetic permeability, low weight, easy installation procedure and practically unlimited availability in various geometries and sizes is considered to be the most effective solutions to all unanswered queries in the construction industry.

2.3 CFRP Laminate:-
CFRP laminates manufactured by CFRP fabrics which are pre-impregnated with a resin and then it is cured for some period before supplying to the site for installation. The properties of the CFRP laminates used in this research are listed in the Table 1.

| Properties | Width = 1.4mm, Thickness =100mm, Design Area = 140mm², Modulus of Elasticity > 165000 N/mm², Ultimate Tensile Strength > 2800 N/mm², Rupture strain = 0.017 mm/mm |

2.4 Test on CFRP Laminate:-
The tests conducted to determine the properties of CFRP Laminates are, a) Tensile strength b) Bond strength of CFRP composite with concrete. a) Tensile Test: The tensile test was carried out using universal testing machine (UTM) by applying uniaxial load at the two ends of the test specimen (laminate) using suitable jaws which are attached to UTM shown in Fig1(a). Failure of specimen was due to rupture as shown in Fig1 (b). The dimension of the test specimen used was confirming to ISO Specifications. The ultimate strength of laminate obtained from tension test was 3002 N/mm² shown in Fig 2.
Fig 1. (a) Uniaxial load at the two ends of the test specimen; (b) Laminate after rupture.

Fig 2. Stress-Strain curve for CFRP laminate.

b) Bond Strength of CFRP composite with concrete: The experimentation was done to evaluate the bond stress to check the efficiency of adhesive in order to know the feasibility of debonding. To determine the bond stress the pull-test was conducted by subjecting the tension force to the free end of the laminate. The details of specimens prepared for pull-test to check the bond strength between concrete and laminate are shown in Fig 3(a) & (b). Each set consists of different bond length of 100mm, 200mm and 300mm. The bond length of 300mm gives the effective bond stress of 2.23N/mm².

Fig 3. (a) Details of Pull-Test Specimen; (b) Prepared specimen for bond test; (c) Testing arrangement for bond strength.

3. DESIGN OF BEAMS

In this research work, a beam is designed to carry a load of 70 kN. The load of 70kN is applied on the beam as two point loads of 35kN each at a distance of one-third of the span from either side of the supports. The dimension of the beam was taken as 200X200X2300mm taking effective span as 2100mm by providing 100mm bearing on either side. The beam is designed to fail in under-reinforced condition. Design procedure was followed by the guidelines of IS: 456-2000. Precautions have been taken such that the beam should not fail in shear. The reinforcement details are shown in Fig.4.

Fig 4: Longitudinal and Cross-section of beam
4. DESCRIPTION OF SPECIMENS

A total of six beams were casted, out of this two beams were taken as control beams (CB) and the remaining four beams are strengthened using CFRP laminate. The strengthened beams are divided into two sets of two beams each i.e. Externally Bonded Laminate (EBL) and Internally Bonded Laminate (IBL). The detailed summary of the beams are shown in Table 2.

Table 2: Description of Test beams

| Beam Group | Description of Specimen | Strengthening Configuration | Reinf Ratio for steel | Reinf Ratio for CFRP Laminate |
|------------|-------------------------|-----------------------------|----------------------|------------------------------|
| CB-1       | Control Beam            |                             | 0.012                | ---                          |
| CB-2       |                         |                             |                      |                              |
| EBL-1      | Externally Bonded Laminate |                           | 0.012                | 0.0021                       |
| EBL-2      |                         |                             |                      |                              |
| IBL-1      | Internally Bonded Laminate |                         | 0.012                | 0.0021                       |
| IBL-2      |                         |                             |                      |                              |

5. PREPARATION OF SPECIMENS FOR STRENGTHENING

5.1 Externally Bonded Laminate (EBL).

The concrete surface at the bottom was grinded using machine grinder. After grinding, the dust and chipped particles were cleaned to make the surface ready for strengthening. CFRP laminates were then cut into a desired length which includes development length. Before applying the epoxy adhesive on concrete surface, the rough side of the laminate was wiped with acetone or solvent to remove the carbon dust by taking proper precautions. The epoxy adhesive consists of Nitobond PC base and Nitobond PC40 hardener. Base and the hardener were mixed thoroughly in the proportion 2:1, then the mixture was applied on the concrete substrate surface as well as rough side of the laminate using rubber spatula. CFRP laminates are placed on the concrete surface by pressing the laminate gently by hand and rolling it by hard rubber roller to remove air voids for proper bonding. Excess adhesive on the sides are removed before it cures. Then it is cured for 7 days before testing. The procedure followed in strengthening of beam using EBL technique is shown in Fig 5.
Fig 5. (a) Preparation of surface for strengthening by grinding.; (b) Cutting of laminate for required length; (c) Epoxy adhesives (Hardener and Base); (d) Mixing of hardener and base; (e) Epoxy adhesive applied on concrete surface using rubber spatula; (f) Placing of laminate on applied adhesive; (g) & (f) Hard rubber roller is rolled on the laminate to remove the air voids.

5.2 Internally Bonded Laminate (IBL).

The cover portion in the bottom surface of the beam is marked to the required dimension of the laminate for cutting a groove. The marked portion was cut in vertical direction and then it was chipped using chisel to prepare a groove of size of 1800mm (length) X 70mm (width) X 10mm (depth). The bottom surface of the groove was grinded using machine grinder. After grinding, the dust and chipped particles were cleaned to make the surface ready for strengthening. The epoxy comprised of base and hardener was mixed thoroughly in the proportion 2:1. The epoxy was filled to the groove upto a depth of 5mm then placed the laminate above the epoxy. Before it hardens fill the remaining portion of groove by epoxy. After the application of laminate for strengthening, the epoxy should be cured for atleast 7 days before testing. The procedure followed in strengthening of beam using IBL technique is shown in Fig 6.

Fig 6. (a) Cutting of marked portion on the beam to prepare a groove; (b) Chipping of concrete; (c) Finishing the chipped surface by grinding; (d) Finished surface having groove size 60X10mm; (e) Filling epoxy to the groove up to 5mm depth; (f) Placing the laminate above the epoxy; (g) Remaining portion of the groove packed with epoxy; (f) Finished surface after strengthening for curing.

6. EXPERIMENTAL SETUP

Two point loading system was adopted for the tests. The specimen was brushed with lime wash to identify crack patterns easily. The setup was carried out using 50-Ton(T) capacity loading
frame. A 50T loading cell was fixed above the jack, which was connected to a digital indicator for measuring the loading increments. Spreader beam (I-Section) was used to transfer the load from loading jack to the specimen. Three digital deflection gauges were placed under the loads and midspan of the specimen for measuring the deflections. Mechanical strain gauges were used to measure the strain at four levels i.e top, center, at the level steel and CFRP reinforcements. The studs were placed at two points using metal paste to the surface of the specimen and these points were referred to as the gauge points. The load was applied on to the specimens using a hand held lever. The strain gauge readings and deflection values were noted for every increment of 2kN load. The experimental setup is shown in the Fig 7.

Fig 7: Experimental Setup of test specimen

7. RESULTS AND DISCUSSIONS

7.1 Study on Ultimate Strength

The results from the experiments are tabulated in Table 3 & 4. According to the experimental results, the strengthened beam shows a higher ultimate strength compared to control beams (CB). In strengthened beams, internally bonded laminate (IBL) technique gives the better result when compared with Externally Bonded Laminate (EBL). The ultimate load ($P_u$) and working load ($P_w$) for EBL technique was increased by 24% when compared with CB. The ultimate load ($P_u$) and working load ($P_w$) for IBL technique was increased up to 73% when compared with CB and 39.5% compared with EBL technique. The cracking load ($P_{cr}$) for EBL technique was increased up to 18% when compared with control beams. The cracking load ($P_{cr}$) for IBL technique was increased up to 53% when compared with CB and 30% compared with EBL technique. The comparative study on ultimate load ($P_u$), working load ($P_w$) and cracking load ($P_{cr}$) has been shown in Fig. 15 to 17. All the strengthened beams were failed due to debonding. The experimental working loads were compared with design working loads which were calculated using the strengthening codes such as ACI 440.2R-08, FIB Bulletin-2001 and CNR-DT 200/2004. The results from experimental work and design codes are tabulated in Table 5. From the comparative study, the IBL technique was emerged as the better strengthening technique, increasing almost 41% of working load ($P_w$) when compared with strengthening codes.

7.2 Study on Load deflection behaviour

Totally three digital deflection gauges were placed under the test specimens in order to note down the deflection values for every 2kN increment of load. In that two deflection gauges are placed under the load and another one under the midspan of the beam. The curve was plotted using mid deflection value with respect to load which is termed as load deflection curve. Using this load deflection curve, the behaviour of the beams has been studied. The load deflection...
The deflection of the test beams were noted at cracking (P_cr), working (P_w) and ultimate loads (P_u) which is shown in Table 4. According to the codal provisions, the serviceability requirements are satisfied for working load. All the strengthened beams have failed due to laminate debonding. In case of strengthened beams using IBL technique, as the internal debonding occurs between laminate and adhesive, the deflection tends to increase drastically for every increment of load and this process continues until the epoxy cover rips off with laminate. The experimental results were compared with design values obtained from strengthening codes such as ACI 440.2R-08, FIB Bulletin-2001 and CNR-DT 200/2004. The deflection under working load from experiments and design code are tabulated in Table 6. All the working deflection (w) values from experiment are less than the values obtained by design codes.

### Table 3: Experimental results of the test specimens

| Beam Designation | Debonding of CFRP | Rupture of CFRP | Deflection at Midspan (u) | Ultimate Load (P_u) | Average Ultimate Load (P_u) | % Increase with reference to control beam |
|------------------|-------------------|-----------------|---------------------------|---------------------|-----------------------------|------------------------------------------|
| CB-1             | -----             | -----           | 14.675                    | 88                  | 92                          | --------                                 |
| CB-2             | -----             | -----           | 15.651                    | 96                  |                             | ----------------------------------------|
| EBL-1            | Yes               | No              | 14.290                    | 112                 | 114                         | 23.91                                    |
| EBL-2            | Yes               | No              | 15.112                    | 116                 |                             | ----------------------------------------|
| IBL-1            | Yes               | No              | 18.925                    | 152                 | 159                         | 72.83                                    |
| IBL-2            | Yes               | No              | 22.786                    | 166                 |                             | ----------------------------------------|

### Table 4: Load and deflection values of all the beams from experiments

| Beam Designation | Grade of concrete (f_c) | P_cr | P_w | P_u | cr | w | u |
|------------------|-------------------------|------|-----|-----|----|---|---|
| CB-1             | 50.87                   | 58.67| 88  | 88  | 0.783 | 4.975 | 14.675 |
| CB-2             | 50.87                   | 64.00| 96  | 96  | 1.055 | 5.846 | 15.651 |
| EBL-1            | 45.76                   | 74.67| 112 | 112 | 2.120 | 8.128 | 14.290 |
| EBL-2            | 45.76                   | 77.33| 116 | 116 | 1.156 | 6.510 | 15.112 |
| IBL-1            | 52.50                   | 101.33| 152 | 152 | 1.982 | 9.692 | 18.925 |
| IBL-2            | 52.50                   | 110.67| 166 | 166 | 1.786 | 11.257 | 22.786 |

### Table 5: Comparison of experimental working load (P_w) with different codes

| Beam Designation | Grade of concrete (f_c) | Experimental | ACI 440.2R-08 | CNR-DT 200/2004 | FIB Bulletin 2001 |
|------------------|-------------------------|--------------|---------------|-----------------|-------------------|
| CB-1             | 50.87                   | 58.67        | 53.10         | 55.41           | 51.79             |
| CB-2             | 50.87                   | 64.00        | 53.10         | 55.41           | 51.79             |
| EBL-1            | 45.76                   | 74.67        | 70.10         | 73.18           | 73.98             |
| EBL-2            | 45.76                   | 77.33        | 70.10         | 73.18           | 73.98             |
| IBL-1            | 52.50                   | 101.33       | 71.43         | 74.83           | 75.34             |
| IBL-2            | 52.50                   | 110.67       | 71.43         | 74.83           | 75.34             |
Table 6: Comparision of experimental deflection ($w_e$) under working load with different codes

| Beam Designation | Grade of Concrete ($f_{ck}$) | Experimental | ACI 440.2R-08 | CNR-DT 200/2004 | Fib Bulletin 2001 |
|------------------|-----------------------------|--------------|---------------|-----------------|-------------------|
| CB-1             | 50.87                       | 4.975        | 6.41          | 7.35            | 7.93              |
| CB-2             | 50.87                       | 5.846        | 6.41          | 7.35            | 7.93              |
| EBL-1            | 45.76                       | 8.128        | 13.67         | 14.36           | 13.16             |
| EBL-2            | 45.76                       | 6.510        | 13.67         | 14.36           | 13.16             |
| IBL-1            | 52.50                       | 9.692        | 14.12         | 14.83           | 13.94             |
| IBL-2            | 52.50                       | 11.257       | 14.12         | 4.83            | 13.94             |

Fig 8: Load v/s Deflection curve-CB-1
Fig 9: Load v/s Deflection curve-CB-2
Fig 10: Load v/s Deflection curve-EBL-1
Fig 11: Load v/s Deflection curve-EBL-2
Fig 12: Load v/s Deflection curve-IBL-1
Fig 13: Load v/s Deflection curve-IBL-2
7.3 Study on Displacement (Deflection) Ductility.

In the structural design the special importance is given for the serviceability criteria. Ductility of the structure is the ability to undergo inelastic deformation by giving sufficient warnings before the structural components fails i.e. it should undergo an excessive plastic deformation without a great loss of its resistance. Deflection (Displacement) ductility was computed using bilinear method and is tabulated in Table 7. From the table 7 it can be observed that, the displacement ductility decreases for all the strengthened beams when compared to control beams. According to strengthened beams are concerned displacement ductility decreases for internally bonded laminate (IBL) when compared with externally bonded laminates (EBL).

| Beam Designation | Grade of Concrete (fck) | Grade of Steel (f_y) | Ultimate Deflection (w) | Deflection at yield Point (\(w_y\)) | Ductility Index \(\mu_d = \frac{\Delta w}{\Delta w_y}\) |
|------------------|-------------------------|----------------------|-------------------------|-------------------------------------|---------------------------------|
| CB-1             | 50.87                   | 500                  | 14.675                  | 3.60                                | 4.07                            |
| CB-2             | 50.87                   | 500                  | 15.651                  | 4.20                                | 3.72                            |
| EBL-1            | 45.76                   | 500                  | 14.290                  | 4.30                                | 3.32                            |
| EBL-2            | 45.76                   | 500                  | 15.112                  | 5.30                                | 2.85                            |
| IBL-1            | 52.50                   | 500                  | 18.925                  | 8.60                                | 2.20                            |
| IBL-2            | 52.50                   | 500                  | 22.786                  | 10.60                               | 2.15                            |
7.4 Study on Debonding Strain in Laminate.

In almost all strengthening codes the rupture strain will not be taken into account for design process. The laminate along with the adhesive is applied on the weaker portion such as cover portion where debonding failure is the major drawback. Hence instead of considering the rupture strain the debonding strain is considered in the design. In this work, the effort has been done in order to increase de-bonding strain by placing the laminate inside the groove in IBL technique. IBL technique shows the significant increase in the debonding strain by delaying the beam from debonding failure which in turn enhances the load by almost 73% compared with control beam and 39% when compared with EBL technique. All the debonding strain values from experiment are more than the values obtained by design codes. The IBL technique emerged as the best technique by delaying the debonding failure by taking more strain as shown in Table 8.

Table 8: Comparison of experimental debonding Strain in laminate at failure with different codes

| Beam Designation | Experimental Result | ACI 440.2R-08 | CNR-DT 200/2004 | Spanish Code STO (BASF) |
|------------------|---------------------|---------------|----------------|------------------------|
| EBL-1            | 0.00765             | 0.00577       | 0.00614        | 0.00696                |
| EBL-2            | 0.00889             | 0.00577       | 0.00614        | 0.00696                |
| IBL-1            | 0.00877             | 0.00618       | 0.00651        | 0.00747                |
| IBL-2            | 0.00912             | 0.00618       | 0.00651        | 0.00747                |

7.5 Failure mode of EBL and IBL technique

EBL Technique: The failure was caused due to pre-mature debonding of laminate at the cover portion shown in Fig 18 (a)  
IBL Technique: The failure caused by ripping off epoxy cover with CFRP laminate. After failure, the beam was inspected by chipping the bottom surface, it was found that there was no rupture of laminate and the failure was due to debonding as shown in Fig 18(b) & (c)

Fig 18. (a) Failure pattern for EBL technique; (b) & (c) Failure pattern for IBL technique.

8. CONCLUSIONS

All the strengthened beams increases the ultimate load carrying capacity compared with control beams. The results from the experimental investigation suggest that, the beam strengthened with IBL technique can significantly increase the cracking (Pcr), working (Pw) and ultimate load (Pu) when compared with EBL technique. The ultimate load (Pu) and working load (Pw) for EBL technique was increased up to 24% when compared to control beams. The ultimate load (Pu) and working load (Pw) for IBL technique was increased up to 73% when compared with control beams and 39.5% compared with EBL technique. The values of deflection under the working load for all the strengthened beams were less than the values calculated from the strengthening codes. The displacement ductility of the strengthened beams reduced in comparison with control beam. In case of strengthened beams using IBL technique, the displacement ductility reduces when compared with EBL technique, hence the IBL technique
gives less warning before it fails. All the strengthened beams were failed due to premature debonding of laminate. The debonding strain in case of IBL technique is higher than the EBL technique, hence the internally bonded laminate (IBL) technique can be effectively used to delay the debonding of laminate which in turn enhances the ultimate load carrying capacity.

REFERENCES

[1]. Mongi Ben Ouezdou, Abdeldjelil Belarbi, and Sang-Wook Bae, “Effective bond length of FRP sheets externally bonded to concrete,” International Journal of Concrete Structures and Materials, Vol. 3, no. 2, pp. 127-131, December 2009.

[2]. J.Yao, J.G.Teng and J.F.Chen, “Experimental study on FRP-to-concrete bonded joints,” Composites: Part B, vol. 36, pp. 99-113, 2005.

[3]. Sang-Kyun Woo, Jang-Ho Jay Kim, Keun-Joo Byun, and Young-Chul Song, “Bond-slip Parameter Determination Procedure of RC Flexure Member Strengthened with Prestressed CFRP Plates,” KSCE Journal of Civil Engineering, vol. 17, no. 1, pp. 179-191, 2013.

[4]. Oguz Gunes, Oral Buyukozturk and Erdem Karaca, “A fracture-based model for FRP debonding in strengthened beams,” Engineering Fracture Mechanics, vol. 76, pp. 1897–1909, 2009.

[5]. Anton Alekseevich Bykov and Aleksandr Vasilyevich Kalugin, “New Model for Evaluation of FRP Debonding Strain for Russian Design Code,” Advances in Materials Science and Engineering, Vol. 2013, Article ID 130162, 11 pages.

[6]. M.R. Esfahani, M.R. Kianoush and A.R. Tajari, “Flexural behaviour of reinforced concrete beams strengthened by CFRP sheets,” Engineering Structures, vol. 29, no. 10, pp. 2428-2444, 2007.

[7]. E. Ferrier, S. Avril, P. Hamelin and A. Vautrin, “Mechanical behavior of RC beams reinforced by externally bonded CFRP sheets,” Materials and Structures, vol. 36, pp.522-529, 2003.

[8]. Mahmoud T. El-Mihilmy and Joseph W. Tedesco, “Analysis of Reinforced Concrete Beams Strengthened With FRP Laminates,” Journal of Structural Engineering, vol. 126, pp. 684-691, 2000.

[9]. Jankowiak, “Analysis of RC beams strengthened by CFRP strips-Experimental and FEA study,” Archives of Civil and Mechanical Engineering, Vol. 12, pp. 376-388, 2012.

[10]. Slobodan Rankovic, Radomir Folic and Marina Mijalkovic, “Effects of RC beams reinforcement using near surface mounted reinforced FRP composite,” Architecture and Civil Engineering, Vol. 8, no. 2, pp. 177-185, 2010.

[11]. ACI 440. 2R-08, “Guide for the Design and Construction of Externally Bonded FRP Systems for Strengthening of Concrete Structures, Michigan, American Concrete Institute, ACI Committee 440, 2008.

[12]. CNR-DT 200/2004, Guide for the Design and construction of Externally Bonded FRP Systems for Strengthening Existing structures and materials, RC and PC Structures, Masonry structure, Italian National Research Council, Rome, Italy, 2004.

[13]. Fib Bulletin 14. Externally bonded FRP reinforcement for RC Structures, 2001.