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# A Comparative Study on the Experimental Results of Strengthened Beams using Externally Bonded Laminate Technique with Strengthening Codes

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**Abstract**

This paper presents the detailed study on the Reinforced Concrete (RC) beams strengthened with Externally Bonded Laminate (EBL) Technique using Carbon Fiber Reinforced Polymer (CFRP) Laminate. All the beams were designed for under-reinforced condition according to IS: 456-2000. Totally four beams were casted, out of this two beams were control beams and remaining two were strengthened beams. The experimental setup was done for four point bending case. The experimental results indicate that, the ultimate load was enhanced by 23.91% compares to control beams. The study was mainly concentrated on the experimental investigation and theoretical investigation. In the theoretical investigation, the ultimate moment values and working deflection values were calculated from the expressions of different strengthening codes. The theoretical and experimental values were compared. The study reveals that the theoretical results show good agreement with the experimental results.

**Keywords**: Carbon Fiber Reinforced Polymer (CFRP), Externally Bonded Laminate (EBL), Laminate, RC Beams

## INTRODUCTION

Strengthening of existing RC beams using CFRP composite materials have been carried out practically for many years in reference to past research work done by various researchers around the world. As an outcome of this, many strengthening techniques have been evaluated from the research papers, practical guidelines and strengthening codes published all over the world. The application of CFRP composites utilized for strengthening the structural component in flexure and shear. These CFRP composites have advantageous properties such as high-strength to weight ratio, corrosion resistance, ease of handling and durability. Use of CFRP composites for strengthening techniques have proved to be an effective technique than other conventional methods of strengthening, but in some instance CFRP strengthening may be uneconomical and also difficult in application. CFRP Composites can be applied externally which is known as Externally Bonded (EB) technique in which the composites are bonded on the surface of the tension zone in the structural members and there is another method which is known as Near Surface Mounted (NSM) Technique in which the composites are internally bonded on the tension zone by providing a groove on the surface and then placing composites inside groove by the help of adhesive, then remaining portion of the groove is filled by adhesives. The structural behaviour of FRP composites used for strengthening has been broadly studied over the last few decades and these research studies have been incorporated in some design guidelines such as European Code Fib Bulletin14-2001; Italian Codes CNR DT 200 R1/2013, CNR-DT 200/2004, American Code ACI 440.2R-08, England Code TR55 Canadian Code ISIS Design Manual No. 3 2007. Although a more number of studies available regarding the FRP composites from past literature, the predictions given by the analytical models and design guidelines are sometime unconvincing and incompatible with the experimental results. Hence to overcome these issues, the researchers from most of the countries are in discussion on the important issues to prepare the improved version of guidelines. The international technical committee STAR 234-DUC 2015 was established in 2009 to discuss the issues related to the use of FRP composites or laminates to strengthen the structural elements. This committee was formed by the team of experts in the field of strengthening from different organization, academic institute, research institute and members involved in the development of codal provisions. The committee members are from the countries such as United States, China, Italy, Spain, Germany, Switzerland, Canada, Japan, Australia and other countries. The discussions done in the committee promoted the latest research developments by conducting annual meetings, the committee analyses different features of the FRP strengthening. They will give the suggestions for the development and improvement of the existing numerical or analytical models and also analyze the feasibility of the newly developed model. These developments are incorporated in their updated or revised codal provision.

## MATERIAL AND PROPERTIES

### Concrete and Steel reinforcement

In this present research work, the mix design for M-40 concrete was done according to IS: 10262-2009. The High Yield Strength Deformed (HYSD) bars were used as the steel reinforcement. The HYSD bars used were of Fe-500 grade which has the tensile strength of 500N/mm$^2$.

**CFRP Laminate**

In this work, the CFRP laminates were used as the strengthening material because of their good properties compared to other FRP composites and their properties are listed in Table 1.

**Table 1.** Properties of Laminate

| Properties |
|---|
| Thickness =1.4mm, Width = 50mm, Design Area = 70mm$^2$, Rupture strain = 0.017 mm/mm, Ultimate Tensile Strength > 2800 N/mm$^2$, Modulus of Elasticity > 165000 N/mm$^2$ |

## DESCRIPTION OF TEST SPECIMENS

Totally four beams were casted, out of this two beams were taken as control beams (CB) and the remaining two beams were strengthened with Externally Bonded Laminate (EBL) Technique.

**Table 2.** Description of Test specimens

| Beam Type | Description of Specimen |
|---|---|
| CB-1,CB-2 | Control Beam |
| EBL-1, EBL-2 | Externally Bonded Laminates |

## DESIGN AND DETAILING OF BEAM

The beam was designed for under-reinforced condition to carry an ultimate load of 70kN. The design was done by splitting the 70 kN load as two point loads of 35 kN each acting at a distance of one-third of the effective span from either side of the supports. The effective span of the beam was taken as 2.1m. The design was done according to IS: 456-2000. The detailing of the beam was done as per the Indian code SP-34 and shown in figure 1.

## CASTING OF TEST SPECIMENS

The formwork was prepared for the clear dimension of 200X200X2300mm. The clear cover of 25mm was provided at the bottom of the formwork. The reinforcement was prepared as per the detailing. The reinforcement was placed inside the form work above the cover block. The concrete mix was done according to the mix proportions. The concrete was poured in layers and the compaction was done with the help of a needle vibrator. The concrete was allowed to set for 24 hours and then formwork was removed carefully. Then the specimen was allowed for moist curing with gunny bags for 28 days.

## APPLICATION OF CFRP LAMINATES

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 was cured for 7 days before testing. The procedure followed in strengthening of beam using EBL technique is shown in Fig 2.

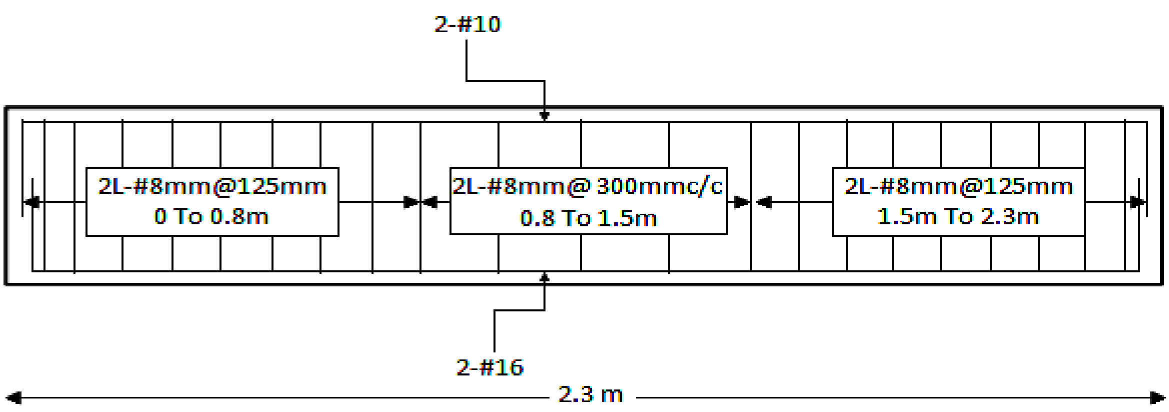


**Figure 1.** Longitudinal section of beam

**Figure 2** (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.

## EXPERIMENTAL INVESTIGATIONS

Test specimens were subjected to two point loading condition for pure bending case. The specimens were painted with lime wash in order to mark the cracks developed on the surface during the experimentation. The setup was carried out with a 100 Ton loading frame. A jack was fixed on top of the specimen to apply load. A 100 ton loading cell was fixed above the jack which was connected to a digital indicator to measure the loading increments. I section was provided to transfer the load from loading jack to the specimen. The deflection at the bottom of the beam was measured using the dial gauges. The effective span of the beam was taken as 2.1m. The beams were named corresponding to the strengthening technique to which they were subjected. Three mechanical dial gauges were used to measure the deflection at one-third distance from the support and at the midspan of the specimen when the load was applied. The load was applied on to the specimens using a hand held lever with uniform increment up to the failure load. The dial gauge readings were noted down to calculate the deflections of the beam. Subsequently the load was incremented manually and the readings of the dial gauge were taken at every 2kN increments. The complete experimental setup is shown in figure 3. All the results from the experimental investigation are tabulated in table 3.

**Figure 3.** Experimental Setup for two point loading

**Table 3.** Experimental results of the test specimens under failure

| Beam Type | Compressive Strength of Concrete($f_{ck}$) in N/mm$^2$ | Ultimate Load ($P_u$) in kN | Mid Deflection ($\Delta_u$) in mm | Working Load ($P_w$) in kN | Working Deflection ($\Delta_w$) in mm | Mode of Failure |
|---|---|---|---|---|---|---|
| CB-1 | 50.87 | 88 | 14.675 | 58.670 | 4.975 | Tension Failure |
| CB-2 | 50.87 | 96 | 15.651 | 64.000 | 5.846 | Tension Failure |
| EBL-1 | 45.76 | 112 | 15.112 | 74.670 | 7.345 | Cover Separation |
| EBL-2 | 45.76 | 116 | 14.290 | 77.330 | 6.517 | Debonding of Laminate |

## THEORETICAL INVESTIGATION

The theoretical investigation of all the beams have been done from various codes such as European Code Fib Bulletin14-2001; Italian Codes CNR DT 200 R1/2013, CNR-DT 200/2004, American Code ACI 440.2R-08, England Code TR55 Canadian Code ISIS Design Manual No. 3 2007. The ultimate moment values and the deflection under the working moments (i.e. working Deflections) are calculated from the available expressions in strengthening codes.

## RESULTS AND DISCUSSIONS

### Experimental Study on ultimate Load

The ultimate load of all the strengthened beams was assessed with control beams shown in table 4. The average ultimate load for the control beams were observed as 92kN. The average ultimate load for strengthened beam was observed as 114kN. The enhancement of ultimate load was 23.91% compared to the control beams.

**Table 4.** Percentage increase in ultimate load

| Beam Type | $F_{ck}$ | Ultimate Load ($P_u$) in kN | Mode of Failure | Average $P_u$ | % Increase Reference to CB |
|---|---|---|---|---|---|
| CB-1 | 50.87 | 88 | Tension Failure | 92 | ------- |
| CB-2 | 50.87 | 96 | Tension Failure | | |
| EBL-1 | 45.76 | 112 | Cover Separation | 114 | 23.91 |
| EBL-2 | 45.76 | 116 | Debonding of Laminate | | |

### Experimental Study on Ultimate Moment (Mu)

The ultimate moment value for two point loading condition occurs under the load and calculated from the expression $\frac{P_u L}{6}$. The ultimate moment values calculated are tabulated in table 5

**Table 5.** Ultimate and Working Moment

| Beam Type | $F_{ck}$ | Ultimate Load ($P_u$) in kN | Ultimate Moment ($M_u$) | Working Moment ($M_w$) |
|---|---|---|---|---|
| CB-1 | 50.87 | 88 | 30.8 | 20.53 |
| CB-2 | 50.87 | 96 | 33.6 | 22.40 |
| EBL-1 | 45.76 | 112 | 39.2 | 26.13 |
| EBL-2 | 45.76 | 116 | 40.6 | 27.07 |

### Comparative study on experimental and theoretical moments.

The values of theoretical and experimental ultimate moments were calculated and tabulated in table 6. The percentage increase in average experimental ultimate moment value of strengthened beams is 8.63% compared to the average theoretical ultimate moment value shown in table 8. The ratio of experimental and theoretical ultimate moments was calculated in order to calculate the mean and coefficient of variance shown table 7. The theoretical ultimate moment values from ACI code shows a good agreement with experimental values compared to all other codes. After the analysis of the above data, it was observed that the ACI code gives the least coefficient of variance of 0.057 having the mean of 0.889.

**Table 6.** Experimental and theoretical ultimate moments of all the beams

| Beam Type | $f_{ck}$ | Experimental ($M_e$) in kN-m | ACI ($M_t$) | Fib ($M_t$) | ISIS ($M_t$) | TR55 ($M_t$) | CNR-DT ($M_t$) |
|---|---|---|---|---|---|---|---|
| CB-1 | 50.87 | 30.8 | 27.50 | 27.38 | 25.45 | 25.84 | 26.74 |
| CB-2 | 50.87 | 33.6 | 27.50 | 27.38 | 25.45 | 25.84 | 26.74 |
| EBL-1 | 45.76 | 39.2 | 36.76 | 38.83 | 35.90 | 35.63 | 36.51 |
| EBL-2 | 45.76 | 40.6 | 36.76 | 38.83 | 35.90 | 35.63 | 36.51 |

**Table 7.** Ratios of experimental and theoretical ultimate moments

| Beam Type | $f_{ck}$ | Experimental ($M_e$) | ACI $\frac{M_t}{M_e}$ | Fib $\frac{M_t}{M_e}$ | ISIS $\frac{M_t}{M_e}$ | TR55 $\frac{M_t}{M_e}$ | CNR-DT $\frac{M_t}{M_e}$ |
|---|---|---|---|---|---|---|---|
| CB-1 | 50.87 | 30.8 | 0.893 | 0.889 | 0.826 | 0.839 | 0.868 |
| CB-2 | 50.87 | 33.6 | 0.818 | 0.815 | 0.757 | 0.769 | 0.796 |
| EBL-1 | 45.76 | 39.2 | 0.938 | 0.991 | 0.916 | 0.909 | 0.931 |
| EBL-2 | 45.76 | 40.6 | 0.905 | 0.956 | 0.884 | 0.878 | 0.899 |
| **Mean** | | | **0.889** | **0.913** | **0.846** | **0.849** | **0.874** |
| **Standard Deviation** | | | **0.050** | **0.078** | **0.070** | **0.060** | **0.058** |
| **Coefficient of Variance** | | | **0.057** | **0.085** | **0.082** | **0.071** | **0.066** |

**Table 8.** Comparison of experimental and theoretical ultimate moments

| Beam Type | ($M_e$) in KN-m | Avg. ($M_e$) | Avg. ($M_t$) | % increase |
|---|---|---|---|---|
| CB-1 | 30.8 | 32.20 | 26.58 | 21.14 |
| CB-2 | 33.6 | | | |
| EBL-1 | 39.2 | 39.90 | 36.73 | 8.63 |
| EBL-2 | 40.6 | | | |

**Comparative study on experimental and theoretical working deflection**

The values of theoretical and experimental working deflection values under working moments were tabulated in table 9. The ratio of experimental and theoretical working deflection values was calculated in order to calculate the mean and coefficient of variance shown in table 10. The theoretical working deflection values from TR 55 code shows a good agreement with experimental values compared to all other codes. After the analysis of the above data, it was observed that the TR55 code gives the least coefficient of variance of 0.208 having the mean of 1.218.

**Table 9.** Experimental and theoretical working deflections under working moment

| Beam Designation | $f_{ck}$ | Experimental ($\Delta_e$) | ACI ($\Delta_t$) | Fib ($\Delta_t$) | ISIS ($\Delta_t$) | TR55 ($\Delta_t$) | CNR-DT ($\Delta_t$) |
|---|---|---|---|---|---|---|---|
| CB-1 | 50.87 | 4.975 | 6.247 | 5.902 | 6.177 | 5.454 | 5.902 |
| CB-2 | 50.87 | 5.846 | 6.247 | 5.902 | 6.177 | 5.454 | 5.902 |
| EBL-1 | 45.76 | 7.345 | 13.642 | 15.23 | 13.74 | 9.810 | 14.30 |
| EBL-2 | 45.76 | 6.517 | 13.642 | 15.23 | 13.74 | 9.810 | 14.30 |

**Table 10.** Ratios of experimental and theoretical working deflection

| Beam Designation | $f_{ck}$ | Experimental ($\Delta_e$) | ACI $\frac{\Delta_t}{\Delta_e}$ | Fib $\frac{\Delta_t}{\Delta_e}$ | ISIS $\frac{\Delta_t}{\Delta_e}$ | TR55 $\frac{\Delta_t}{\Delta_e}$ | CNR-DT $\frac{\Delta_t}{\Delta_e}$ |
|---|---|---|---|---|---|---|---|
| CB-1 | 50.87 | 4.975 | 1.256 | 1.186 | 1.242 | 1.096 | 1.186 |
| CB-2 | 50.87 | 5.846 | 1.069 | 1.010 | 1.057 | 0.933 | 1.010 |
| EBL-1 | 45.76 | 7.345 | 1.857 | 2.074 | 1.871 | 1.336 | 1.947 |
| EBL-2 | 45.76 | 6.517 | 2.093 | 2.337 | 2.108 | 1.505 | 2.194 |
| **Mean** | | | **1.569** | **1.652** | **1.569** | **1.218** | **1.584** |
| **Standard Deviation** | | | **0.485** | **0.652** | **0.501** | **0.253** | **0.575** |
| **Coefficient of Variance** | | | **0.309** | **0.395** | **0.319** | **0.208** | **0.363** |

## CONCLUSION

- The average ultimate load for the beams strengthened with EBL Techniques was increased by 23.91% when compared to control beams.
- The experimental average ultimate moment for the beams strengthened with EBL Techniques was increased by 8.63% when compared to average theoretical ultimate moment.
- All the working deflection values of control and strengthened beams satisfy the codal guidelines.
- The additional tension stiffening of laminate reduces the deflection. Hence, the serviceability requirement satisfies the codal guidelines.
- The experimental moment values were higher than theoretical moment values.
- The experimental working deflection values were less than the theoretical working deflection values.
- The theoretical results show good agreement with experimental results.
- The theoretical ultimate moment values calculated from ACI code gave the best prediction with experimental values compared to all other codes.
- The theoretical working deflection values calculated from TR55 code show a good agreement with experimental values compared to all other codes.

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