# CFRP PLATES AS NEGATIVE MOMENT REINFORCING IN STRENGTHENING OF RC BEAMS

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## 1. Introduction

Using carbon fiber reinforced polymer (CFRP) laminates has proved to be an effective means of upgrading and strengthening reinforced concrete (RC) beams. However, premature failure such as peeling failure and laminate separation can significantly limit the capacity enhancement and prevent the full ultimate flexural capacity of the strengthened beams from being attained. Although many in situ RC beams are of continuous construction, there has been very little research into the behavior of such beams with external reinforcement. In addition, most design guidelines were developed for simply supported beams with external fiber reinforced polymer laminates. In this context, this research attempts to address an important issue that is encountered in strengthening the negative moment regions of RC continuous beams. In flexural strengthening of reinforced concrete beams with epoxy-bonded CFRP plates, local failure in the concrete layer between the steel reinforcement and the composite plate has been observed in experiments. This type of failure prevents the strengthened beam from reaching its ultimate flexural capacity, and therefore it must be included in design considerations. The negative moment region or the support region of continuous reinforced concrete beams is a critical one due to the simultaneous occurrence of maximum moment and shear. The testing program in this research demonstrated the feasibility of strengthening reinforced concrete beams in negative moment region using externally bonded CFRP plates. The primary interest was the achievement of full flexural capacity of the strengthened beams. Several strengthening schemes were conducted in an effort to eliminate the premature failures emanating from the zone of plate curtailment.

## 2. Experimental Program

A total of five half-scale, reinforced, simply supported beams with an overhanging (cantilever) portion were strengthened using CFRP plates. All beams had the same dimensions and flexural and shear reinforcement. One of the tested specimens was tested without any strengthening and considered as the control specimen. The rest specimens were strengthened with CFRP strips using different technique and then tested until complete failure. All specimens were subjected to point loading (using a hydraulic actuator) in the overhanging portion at distance of 400-mm from the free end of each specimen. Each beam was instrumented with five electrical resistance strain gauges, three horizontal Pi-gauges (to measure the strain in concrete), four vertical Linear Variable Distance Transducers, LVDT's (to record deflection), and the load cell (to measure the load) at the point of application of the load. The effect of different parameters such as strengthening technique was evaluated and compared with that predicted by control specimens. Detailed discussion of the materials properties, fabrication of the test specimens, test setup and procedure were given by the author elsewhere.

## 3. Experimental Results and Discussion

The test results of the specimens are summarized in table 1.

### 3.1. Deflections

The strengthened specimens experienced less deflection due to the addition of CFRP strips. As expected, specimen **B2SU** experienced the lowest deflection, while the control specimen experienced the highest deflection. The lowest deflection of the specimen **B2SU** is attributed to its high flexural stiffness. The decrease in deflection was depending on the strengthening technique. Differences in deflections among the strengthened beams started just above the cracking load, where the CFRP plates are effective in increasing the stiffness of the beams.

### 3.2. Cracking Behavior and Failure Modes

The control specimen failed in the classical flexural failure mode, which is characterized by yielding of the tension steel followed by the crushing of concrete in compression zone. The strengthened beams also exhibited flexural failure, and all beams failed in tension. The presence of vertical or continuous layers of CFRP sheets at the ends of the CFRP strips limited the propagation of the cracks, high longitudinal shear, and transverse normal stresses at the plate ends and prevents the CFRP plate's separation. This method of fixation of the plate ends force the beams to failure in a flexural mode. The strengthened specimens displayed relatively better cracking behavior until failure. They showed less intensity and spread of cracking compared to the control specimen. Also the restraints caused by the CFRP strips at the tension side of the concrete, especially in case of **B2SC** and **B2SU**, forced the flexural cracks to start away from the extreme tension fiber. Specimen B2SU failed by the onset of delamination. The CFRP strips underwent splitting through their mid-thickness followed by delamination. The splitting of strips on specimen B2SU suggests that the presence of vertical sheets at the plate ends provided a stronger surface for the CFRP strips than the use of C sheets. It can be also noted that the use of vertical sheets at the plate ends precluded the shear/tension delamination. Peeling of the C-wrap was observed in specimens B1TC and B2SC when the load was nearing ultimate.

### 3.3. Strains in Concrete, Steel, and CFRP

In the unstrengthened beam, the stress in steel bars increased until the steel reaches its yield point. Thereafter, a large portion of any extra stress is absorbed by large deformations in the steel, which lowers the increase of concrete compressive strain. In strengthened beams, tensile stresses are shared between the steel bars and the strengthening plates, so the stresses carried by the steel bars will be less and may not reach the yield strength of steel. Therefore, concrete strains (measured at a depth of 20 mm away from the extreme compression fiber) in the strengthened beams are higher than those in the control beam at the same load.

### 3.4. Stiffness and Ductility

It can be seen that strengthening the beams with CFRP strips resulted in an increase in the stiffness values. Table 2 shows the ductility index (expressed by the ratio of inelastic energy to the total energy) of all the test specimens.

## 4. Conclusions

Based on the experimental results discussed in this paper, the following can be concluded:
(1) The maximum increase in the load carrying capacity of the beam due to strengthening was observed to be 35% with respect to corresponding control beam. (2) The use of CFRP vertical layers or strips at the plate ends can help to further reduce deflections and to further increase ultimate load carrying capacity. (3) The onset of delamination with concrete cover failure (shear/tension delamination) is the critical mode of failure for most strengthened beams. (4) All the strengthened beams exhibited less ductility than the corresponding unstrengthened control beam. (5) The CFRP strengthening strips remain under stressed at the failure load due to the early onset of delamination from the concrete surface.

Table 1 Test Specimens, Concrete Strength, Ultimate Loads & Corresponding Deflection, and Mode of Failure

| Specimen Designation | 28 Days $f_{cu}$ (MPa) | Variable Parameters | | Test Results | | Failure Modes |
|---|---|---|---|---|---|---|
| | | Location of CFRP Plates | End Fixation | Ultimate Load ($P_u$) in KN | Corresponding Deflection (mm) | |
| B000 | 26 | ------ | ------ | 89.8 | 60.2 | Flexural |
| B1TC | 27 | Top | Continuous C Strip | 110 | 40.2 | Splitting* |
| B1TU | 25 | Top | Indivedual U Strips | 100 | 32.2 | Splitting* |
| B2SC | 27 | Sides | Continuous C Strip | 121 | 30 | Splitting* |
| B2SU | 25 | Sides | Indivedual U Strips | 110 | 28.1 | Splitting* |

*** Strips underwent Splitting through their midthickness followed by delamination**

Table 2 Ductility Index of Tested Beams

| Test Specimen | Ductility Index, % |
|---|---|
| B000 | 80 |
| B1TC | 70 |
| B1TU | 72 |
| B2SC | 66 |
| B2SU | 69 |