Hybrid and External strengthening of T-Reinforced Concrete Beams under Negative Bending Moment Using Steel Plates and CFRP

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Abstract. This study compares external bonded techniques and hybrid strengthening when used. The percentage of material for strengthening is different. This study suggests using a steel plate and a CFRP sheet to strengthen the reinforced concrete beam applied with two methods. Nine reinforced concrete T-beams divided into four groups were cast and tested under a negative bending moment. Two groups strengthened by external bonded and two groups strengthened by hybrid strengthening. All beams had the same amount of reinforcement and dimensions of 2300 mm length, an overall depth of 265 mm (200 mm web depth and flange thickness of 65 mm), an effective flange width of 390 mm, and a 130 mm web width. The strengthening by steel plate or CFRP sheet and steel plate and CFRP together, increasing the first cracking load of 40% of the span length is higher than 80%. Also, the decrease of deflection is higher than 80%. At the same time, the ultimate load of 80% is higher than 40%. CFRP sheet in strengthening with 40% lead increase in the first cracking load and ultimate load is better than steel plate when the percentage 40%, while strengthening by steel plate with 80% lead increase in the first crack load and ultimate load is better than CFRP sheet when the ratio 80%.

Keywords: Hybrid; strengthening; steel plates; CFRP.

1. Introduction
Deterioration is a natural law that affects building structures from the earliest structures to the most modern structures. As a result, in recent decades, the global demand for upgrading and strengthening has increased. Reinforced concrete reinforcement is a standard and essential feature in civil engineering, becoming obtainable options for those structures that are more economical to strengthen than to demolish. Therefore, techniques of strengthening have been proposed and developed over years of practical and laboratory work. External strengthening gives practical advantages compared to other rehabilitation methods include; low cost, ease of maintenance, and the ability to strengthen part of the structure while still in use. However, this method's disadvantage is the premature de bonding of the externally bonded strips, which is a brittle and undesired mode of failure. In civil engineering, the two most common materials used for rehabilitation and strengthening RC structures are steel and fiber-reinforced polymers (FRP). Each material for advantages for external bonded application. Plate is one of the most common materials for strengthening reinforced concrete beams [1]. The use of externally bonded steel plates and Carbon fiber-reinforced polymer is becoming a common means of strengthening to extend deficient structures' service life.

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Using externally bonded (EB) carbon fiber reinforced polymer (CFRP) is today a popular technique to improve the flexural capacity and shear capacity of reinforced concrete (RC) members. The first application of bonded CFRP composites for flexural strengthening of reinforced concrete bridges occurred in the late 1980s [2]. Although the externally bonded (EB) CFRP enhances the ultimate load-bearing capacity of RC beams, tests have proven limitations in the extent of obtainable increase in capacity due to the bonded laminate's premature debonding initiated at intermediate cracks [3]. Externally bonded steel plates have been used to strengthen or repair bridges and buildings in many countries worldwide, including South Africa, Switzerland, France, USSR, Japan, United Kingdom, Australia, Belgium, and Poland, because this strengthening technique has not been widely researched or implemented in the United States [4].

It is very effective for increasing the flexure and shear. Strengthening by steel plate popular method due to its availability, cheapness, uniform materials properties (isotropic), ease to work, high ductility, and high fatigue strength. CFRP material had proved to be more efficient than other composites when applied to concrete as an external reinforcement because of its enhanced durability characteristics compared to glass or aramid and it is relatively high elastic modulus. Khalaf, Q. (2015) [5] In this study, the parameter included type of strengthening (shear or flexural), the technique of strengthening (concrete jacketing, steel plating), and the type of connections to prevent laminar shear between the old concrete and the strengthening elements (mechanical or chemical. In this work, an attempt was made to assess the behavior of reinforced concrete T- beams strengthened with different strengthening techniques using steel plate and CFRP sheet subject under a negative bending moment.

2. Experimental work

2.1 Description of beams specimens and details
Nine reinforced concrete T-beams were cast and designed to fail in flexure. All specimens have the same cross-section and amount of reinforcement. They had an overall length of 2300 mm and a clear span (L) of 2000 mm, the overall depth of 265 mm, i.e., 200 mm depth of web and 65 mm depth of flange, an effective flange width (b) of 390 mm and a 130 mm web width (bw). The beam specimens were reinforced with 4-Ø12 steel bars as longitudinal tension reinforcement at the bottom face of T-beams' flange. Also, to prevent transverse bending failure of the flange, transverse reinforcement (6 mm diameter bars at 250 mm c/c spacing) was used. So, to avoid shear failure of the section, 10 mm diameter stirrups at 125 mm c/c spacing were provided in the web. The beam details are shown in Figure 1 and figure 2. Table 1 sum up the properties of the used steel reinforcement.

![Figure 1. Details of beams.](image1)

![Figure 2. Cross-section of beams.](image2)

2.2 Concrete ingredients
Ordinary Portland cement is usually used in the production of normal strength concrete. Tasloja cement was chosen to be used in this work. This cement was found to satisfy the ASTM C150-16 [7]. It should be mentioned that prolonging the curing period was adopted to provide enough time for C2S to hydrate in an adequate amount to acquire the necessary compressive quality. Regular sand taken from Al-Rahalia region(zone) is utilized as a fine aggregate, while crushed gravel from the Al-Nibaey
region (zone) was used to be the coarse aggregate with (14 mm) maximum size. Both fine and coarse aggregate were fulfilling the ASTM C33-11 specification limits [8].

| Table 1. Details of mix design. |
|--------------------------|------------------|-----------------|-------------------|-----------------|-------------------|
| Mix no.  | Cement content (kg/m³) | Sand content | Gravel content | Water (kg/m³) | Cylinder Compressive Strength $f'_c$ (MPa) |
| 1       | 370                 | 750           | 792          | 220          | 24.4               |
| 2       | 400                 | 750           | 780          | 210          | 27.9               |
| 3       | 420                 | 750           | 780          | 210          | 31.3               |

2.3 Material using in strengthening

The steel plate was used in the study of two different thicknesses 1 mm and 2 mm. To evaluate yield and ultimate tensile strengths according to E8/E8M–09 and ASTM A36/A36M–14 [9]. The tests were conducted using the universal testing machine Jet Materials Ltd. Company that has 1000 kN capacity available at the Laboratory of Structural Engineering \ College of Engineering/Diyala University. Test results are shown in Table 2.

| Table 2. Tensile properties of steel plate. |
|---------------------------------------------|
| Nominal Steel plate thickness (mm) | Average of yield tensile strength (MPa) | Average of ultimate tensile strength (MPa) | Average of modulus of elasticity (GPa) | Elongation at ultimate stress (%) |
|-------------------------------------------|----------------------------------------|------------------------------------------|---------------------------------|---------------------------------|
| 1mm                                       | 300                                    | 410                                      | 200                             | 20                              |
| 2mm                                       | 312                                    | 470                                      | 201.425                         | 23                              |

Woven carbon fiber fabrics for structural strengthening were used for outside strengthening of the tested beams. This type is confidential as mid-strength carbon fiber, as shown in reported by the manufacturer. It is unidirectional; the weft is 1% of total areal weight for keeping the fibers dependable together; the weft material as reported by the manufacturer is white thermoplastic heat-set fibers, and the width of the fabric roll is 50 cm and 100 cm. table 8 shows the technical properties of carbon fiber reinforced (CFRP) from SikaWrap®-300 C*.

| Table 3. The technical properties of carbon fiber reinforced (CFRP) from SikaWrap®-300 C* |
|-----------------------------------------------|
| Areal Weight                                 |
| 300 g/m² ± 15 g/m²                          |
| Mechanical/ Physical Properties Laminate     |
| With Sikadur®-300 Laminate thickness 0.167 mm per layer: |
| Ultimate load: 3200 kN/mm width per layer    |
| Tensile E-modulus: 225,000 N/mm² (based on typical laminate thickness of 1.0 mm) |

* These data are listed in the catalogue of the manufacture.

CFRP manufacturer recommends Sikadur®-330 (impregnation resin) to bond CFRP to the concrete. Sikadur®30LP (epoxy adhesive) and were used in this study for the bonding of steel plates. table 9 shows the data of Sikadur®-330 and Sikadur®-30LP.

2.4 Mix design

The concrete mix was designed as recommended by ACI Committee 213.2R-03 [10], many trial mixes were made to reach the target of obtaining the most suitable mix. A proportion by weight of concrete was used in all specimens (1:1.7:1:1.8) is taken for (cement; sand; coarse aggregate) with water-cement ratio of 0.5.
Table 4. Sikadur®-330 and Sikadur®-30LP product data*

| Product Data       | Sikadur®-330                                                                 | Sikadur®-30LP                                                                 |
|--------------------|------------------------------------------------------------------------------|------------------------------------------------------------------------------|
| Chemical Base      | Density 1.30 kg/l ± 0.1 kg/l (Parts A+B mixed) (at +23°C)                    | 1.65 kg/l±0.1 kg/l (Parts A+B mixed) (at +23°C)                              |
| Tensile Strength   | 33.8 N/mm² (7 days at +23°C)                                                 | 10-18 mm²                                                                   |
|                    | Flexural: 3800 N/mm² (7 days at +23°C)                                       | Compressive (10,000 N/mm² (7 days at +25°C)                                  |
|                    | Tensile: 4500 N/mm² (7 days at +23°C)                                        | Tensile: 10000 mm (7 days at +25°C)                                         |
| E-Modulus          | Flexural: 3800 N/mm² (7 days at +23°C)                                       | Compressive (10,000 N/mm² (7 days at +25°C)                                  |
|                    | Tensile: 4500 N/mm² (7 days at +23°C)                                        | Tensile: 10000 mm (7 days at +25°C)                                         |
| Mixing ratio       | Part A: Part B = 4:1 by weight                                               | Part A: Part B =3:1 by weight                                                |

* These data are listed in the catalogue of manufacture

2.5 Details of Specimens
The definition of symbols used in the designation of tested beams is given in Table 5.

Table 5. Definition of used symbols.

| Symbol | Meaning                                                                 |
|--------|------------------------------------------------------------------------|
| R      | Reference beam                                                         |
| P2     | Using steel plate with thickness 2 mm                                   |
| C2     | Using CFRP with two layers                                             |
| PCP2   | Poison steel plate one side of flange and CFRP at mid with (2 mm thickness and two layers) |
| CPC2   | Poison CFRP on the side of flange and steel plate at mid with (2 mm thickness and two layers) |
| P1     | Using steel plate with thickness 1 mm                                   |
| C1     | Using CFRP with one layer                                              |
| PCP1   | Poison steel plate one side of flange and CFRP at mid with (1 mm thickness and one layer) |
| CPC1   | Poison CFRP on the side of flange and steel plate at mid with (2 mm thickness and two-layer) |

3. Beam fabrication, test setup, and instrumentation
In the wooden molds, reinforcing cages were first put in. To achieve adequate compaction, beams were cast, and immersion-type vibrators were used. Six 150x300 mm concrete cylinders were cast for every batch of concrete. The beams and control specimens were removed the next day and healed in a moist atmosphere for 28 days using a damp blanket; they were air-dried in the lab. Each beam was whitewashed for ease of crack detection before testing. In Figure 3, the test arrangements of beams are shown. The beams were simply supported over a span of 2300 mm, and the loads were applied using a 600 kN hydraulic testing system (Jet Materials Ltd. Company). Beams under two-concentrated forces have been tested. All of them were at a distance of 100 mm from the support. The deflected shape of the beam, that is, measured by three dial gauges at the midspan and under each concentrated force applied.

Figure 3. Hydraulic machine used to test all specimens
4. Test procedure
By setting the support positions and loading points, the specimens were prepared for testing. Below the middle and under the loading points of the test specimen bottom face, the dial gauges were fixed. Bearing plates of 20×100×450 mm were used at loading and supporting points to prevent local direct load accumulation on concrete. The monotonic-static loads, before failure, were subjected to the specimens in successive stages. The load was halted during each stage until the necessary measurements were reported (progress of cracks, crack width, strain readings, and deflection at the midspan and under the tested specimen’s loading points). When the total load on the specimen started to drop off, the testing process was accomplished.

5. Experimental results and discussion
5.1 Deflection Behavior
In Figures 4 to 11, the load-deflection behaviors of the three groups are shown. The deflection is linearly increased with the load-applying increase in the pre-cracking point. Subsequently, the stresses in concrete and steel are supposed to be relatively small, and both concrete and steel materials are in the elastic part of their corresponding responses [11,12].

![Figure 4. Comparison of load-deflection curves between the reference beam with P2.](image1)

![Figure 5. Comparison of load-deflection curves between the reference beam with specimen C2.](image2)

![Figure 6. Comparison of load-deflection curves between the reference beam with specimen P1.](image3)

![Figure 7. Comparison of load-deflection curves between the reference beam with C1.](image4)
Figure 8. Comparison of load-deflection curves between the reference beam with PCP2.

Figure 9. Comparison of load-deflection curves between the reference beam with CPC2.

Figure 10. Comparison of load-deflection curves between the reference beam with PCP1.

Figure 11. Comparison of load-deflection curves between the reference beam with CPC1.

5.2 Effect 40% and 80% of Length of Span and Width of Flange on Efficiency Steel Plate

Figure 12 and 13 found that a 40 percent reinforced beam (P2) has a 120 percent increase in first crack load over a non-strengthened beam (R) and a 4.39 percent increase in ultimate load. Although an 80 percent reinforced beam (P1) increases the first crack load by 66.6 percent and the ultimate load by 20%, P2 had a higher first crack load than P1, but P1 had a higher ultimate load.
Figure 12. First crack load and ultimate load of beam strengthened by steel plate (40% and 80%).

Figure 13. Deflection of beams strengthened by steel plate (40% and 80%).

5.3 Effect 40% and 80% of length of span and width of flange on efficiency CFRP

Figure 14 and 15 found that a 40 percent strengthened beam (C2) has a 133 percent increase in first crack load and a 10.43 percent increase in ultimate load over a non-strengthened beam (R). As compared to un-strengthened beams, strengthened beams have an 80 percent (C1) increase in first crack load with a 16 percent increase in ultimate load, C2 had a higher initial crack load than P1, but C1 had a higher ultimate load [13].

Figure 14. First crack load and ultimate load for strengthened beam strengthened by CFRP with 40% and 80%.

Figure 15. Deflection of beam strengthened by CFRP with 40% and 80%.

5.4 Effect of using different materials with percentage 40%

Figures 16 and 17 showed that the steel plate has a higher first crack load and ultimate load than the CFRP sheet. Steel plate deflection is also smaller than CFRP.
The impact of different materials and different percentages of each material has been investigated in this work. When a CFRP-strengthened beam and a steel plate with amount are the same, however, the material's location adhesive varies [14]. When the percentage is the same, one beam is strengthened by an adhesive steel plate on the middle and CFRP adhesive on the side of the flange (CPC2), whereas adhesive CFRP strengthens the other beam on the middle and steel plate adhesive on the side of the flange (PCP2), and the effect of location adhesive material is examined. It can be seen in Figures 18 and 19. When the first crack on a steel plate (CPC2) was higher than the first crack on a CFRP plate (PCP2), the ultimate load on (PCP2) was higher than CPC2. PCP2 had a lower deflection than CPC2 [15].

6. Conclusion

- Two-layer CFRP sheet reinforcement resulted in a higher first cracking load and lower deflection than one-layer CFRP sheet reinforcement.
- As opposed to controlling specimens, using a 2 mm thick steel plate with a 40 percent length span and width of flange resulted in a 120 percent improvement in the first cracking load, a 4.39 percent increase in ultimate load, and a 47.8 percent decrease in deflection. As compared to the control specimens plate, using the thickness (1 mm) and 80 percent length range and width of flange for strengthening resulted in a 66.6 percent increase in first cracking load, a 20% increase in ultimate load, and a 41.22 percent decrease in deflection.
If steel plate or CFRP sheet reinforcement is used, the rise in the first cracking load of 40 percent of the span length is greater than 80 percent. Furthermore, the reduction in deflection is more significant than 80%. The ultimate load of 80 percent is higher than the load of 40% [17].

Using CFRP sheet for strengthening with a 40% lead increase in the first cracking load and ultimate load is better than using steel plate when the percentage is 40%, whereas using steel plate for strengthening with an 80% lead increase in the first crack load and ultimate load is better than CFRP sheet when the percentage is 80%.

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