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Full Length Research Paper

Strengthening of reinforced concrete (RC) beams with prefabricated reinforced concrete (RC) plates

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Reinforced concrete (RC) beams which are insufficient in terms of shear and flexural capacities are strengthened by various methods. Steel and fibre reinforced polymer (FRP) plate bonding methods are very widely used in strengthening of beams. Strengthening methods such as bonding steel and FRP plates have deficiencies as corrosion, fire and buckling. In this work, it is aimed strengthening of damaged RC beams using prefabricated RC rectangular and U cross-sectional plates. The rectangular cross-sectional plates were bonded to the bottom sides of the beams by rods and epoxy. The plates having U cross-section were bonded to the three sides of the beams. The strengthened beams were incrementally loaded up to maximum load capacities. The load carrying capacity of the beams increased 41% with the strengthening rectangular cross-sectional plates, however when the U cross-sectional plates were used, the capacity increased up to 76%. The experimental results were compared with the theoretical values. In addition, post-elastic strength enhancement and displacement ductility of beams were investigated. The advantages of this method do not require shuttering, concrete and steel workmanships in situ. Also, the application of this method is very easy and economic. For these reasons, this method should be preferred against other methods.

Key words: Prefabricated reinforced concrete (RC) plate, strengthening, experimental, theoretical, ductility.

INTRODUCTION

The existing concrete structures and/or elements maybe damaged by chemical processes due to aggressive environment, excessive loading and poor initial design. It becomes both environmentally and economically preferable to repair or strengthen rather than rebuilt them. The choice between these and rebuilt is based on specific factors of each individual case, but certain issues are considered in every case. The strengthening of these beams would be desirable if rapid, economic, effective and simple strengthening techniques are available. Different methods are available for strengthening of existing concrete structures and/or elements. These are bonding with steel plates (Swamy et al., 1987, 1989; Barnes et al., 2001; Sevuk et al., 2005; Adhikary and Mutsuyoshi, 2006; Arslan et al., 2008; Su et al., 2010), fibre reinforced polymer (FRP) sheets (El-Mihilmy and Tedesco, 2000; Buyukozturk and Karaca, 2002; Eshwar et al., 2004; Lu et al., 2005; Pham et al., 2006; De Lorenzis and Teng, 2007; Ozcan et al., 2009), external pre-stressing, external post tensioning and additional concreting (Diab 1998). The plate bonding technique is becoming preferable for strengthening due to several advantages, such as easy construction work, and minimum change in the overall size of the structure after plate bonding. The disadvantage of this method, however, is the danger of corrosion at the adhesive-steel interface, which adversely affects the bond strength (Sevuk et al., 2005).

Swamy et al. (1987) researched the effect of glued steel plates on the first cracking load, cracking behavior, deformation, serviceability, and ultimate strength of RC beams. Adhikary and Mutsuyoshi (2006) presented the results of a parametric study accounting for the effects of plate depth/beam depth ratio, plate thickness, concrete strength and internal shear reinforcement ratio. The

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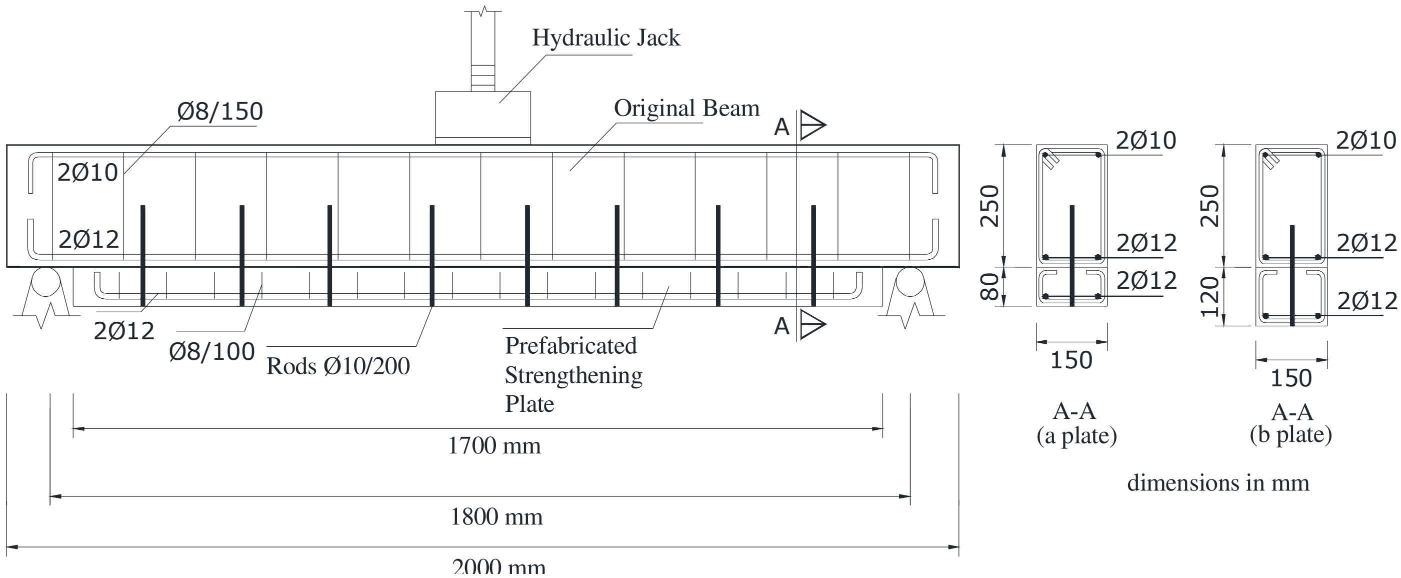

Figure 1. The strengthening with "a and b" plates of the first type beams named "A".

effects of each parameter on shear strength of beams with web-bonded steel plates were discussed. Finally, a design formula to compute the shear strength of beams with web-bonded continuous steel plates was presented. A comparison between the shear strengths computed using the proposed formula and FEM as well as the experimental results was made. Camata et al. (2006) studied the brittle failure modes of RC members strengthened in flexure by FRP plates. Both midspan and plate end failure modes were investigated. The finite element analyses were based on nonlinear fracture mechanics. The model considered the actual crack pattern observed in the tests by using a smeared and an interface crack model. They showed how concrete cracking, adhesive behavior, plate length, width and stiffness affect the failure mechanisms. The numerical and experimental results showed that debonding and concrete cover splitting failure modes occur always by crack propagation inside the concrete. Arslan et al. (2008) investigated the effectiveness of flexural strengthening with continuous horizontal steel plates and load–deflection behavior of rectangular section RC beams after retrofitting. These retrofitted RC beams were tested in the same conditions and the contribution of the repairing and strengthening techniques on load-carrying capacity were investigated. Results obtained from a three-dimensional nonlinear finite element analysis (NLFEA) were compared to the results of experiments and proposed an equation for the calculation of ultimate load capacities. Ceroni (2010) presented the results of an experimental program of RC beams equipped of external strengthening made of carbon FRP sheets or Near Surface Mounted FRP carbon bars. Monotonic and cyclic loading histories were applied according to a four-point test scheme. Moreover end or distributed U-shaped anchoring devices were applied when the strengthening was made of FRP carbon sheets. Comparisons between experimental and theoretical failure loads were discussed.

The objectives of this work are to investigate the effectiveness of flexural and shear strengthening with prefabricated RC plates having three different cross-sections and load–displacement behavior of RC beams after strengthening. The first and second type prefabricated rectangular cross-sectional plates were used to increased flexural capacity of beams. The third type prefabricated U cross-sectional plate was to increased flexural and shear capacity of beams. Experimental results were compared with theoretical results obtained according to ACI 318 and TS-500 (2002).

It is thought that the strengthening method proposed can be useful, practical and reliable for a building or a bridge where similar beam sizes exist.

MATERIALS AND METHODS

Experimental study

Two types of RC beam with the 150x250 mm dimensions were produced in the laboratory. The first type beams named as "A" had stirrups with 8 mm diameter and 150 mm interval. The second type beams named as "B" had stirrups with 8 mm diameter and 250 mm interval. From each type, three beams were produced. The first type beams were named as A1, A2 and A3. The second type beams were named as B1, B2 and B3. The beams were reinforced with two Ø10 bars (10 mm in diameter) in the compression zone, two Ø12 bars (12 mm in diameter) in the tension zone, as shown in Figure 1.

Figure 2. The implementing of Hilti and anchorage rods.

Figure 3. The loading of the strengthened beam.

Two type rectangular cross-sectional prefabricated RC strengthening plates were shown in Figure 1. The plates with 80 and 120 mm in thickness were reinforced with two Ø12 bars (12 mm in diameter) in the tension zone. Stirrups of 8 mm in diameter and 100 mm in interval were applied (Figure 1). The first type plate named as "a" was bonded to the bottom face of the beam by epoxy called "HILTI HIT-RE 500" and anchorage rods.

Before the rods of 10 mm in diameter were applied, the holes of 12 mm in diameter on the bottom faces of the beams and strengthening plates were drilled. These holes were filled with "Hilti". To each hole, a rod was driven about 150 mm into the beam (Figure 2). The second type plate named as "b" is bonded to the beams as "a" plate. The first type strengthening plate was used once; the second type strengthening plate was used twice in the experiments. The loading of the strengthened beam was as shown in Figure 3.

The third type of strengthening application was with U cross-sectional prefabricated RC strengthening plates (Figure 4). The plates with 80 mm in thickness were reinforced with two Ø12 bars (12 mm in diameter) in the tension and compression zones. Stirrups of 8 mm in diameter and 150 mm in interval were applied (Figure 4). The strengthening plates were bonded to the three faces of the beams by epoxy based glue called "HILTI HIT-RE 500" and anchorage rods. Before the rods of 10 mm in diameter were applied, the holes of 12 mm in diameter on the two sides and bottom faces of the beams and strengthening plates were drilled (Figure 4). These holes were filled with "Hilti". To each hole, a rod was driven about 150 mm into the beam. The loading of the strengthened beam is shown in Figure 5.

Materials

Table 1 shows the properties of the beams and plates. Three samples were taken from each type of reinforcement. The tensile tests were carried out, and the yield strength and Young's modulus of these samples summarized (Table 2). The technical properties of epoxy were detailed in Table 3.

Theoretical model

Finding of theoretical failure loads for strengthened and un-strengthened beams

The flexural demand should be computed with the load factors according to ACI 318 and TS500 (2002). The moment capacity for a rectangular RC member strengthened with prefabricated plate is given by Equation 2, where the moments of the internal beam forces are summed about the neutral axis. The equilibrium of internal and external moments is shown in Figures 6 and 7.

$$0,85 f_c b_w k_1 c = A_s f_s \quad (1)$$

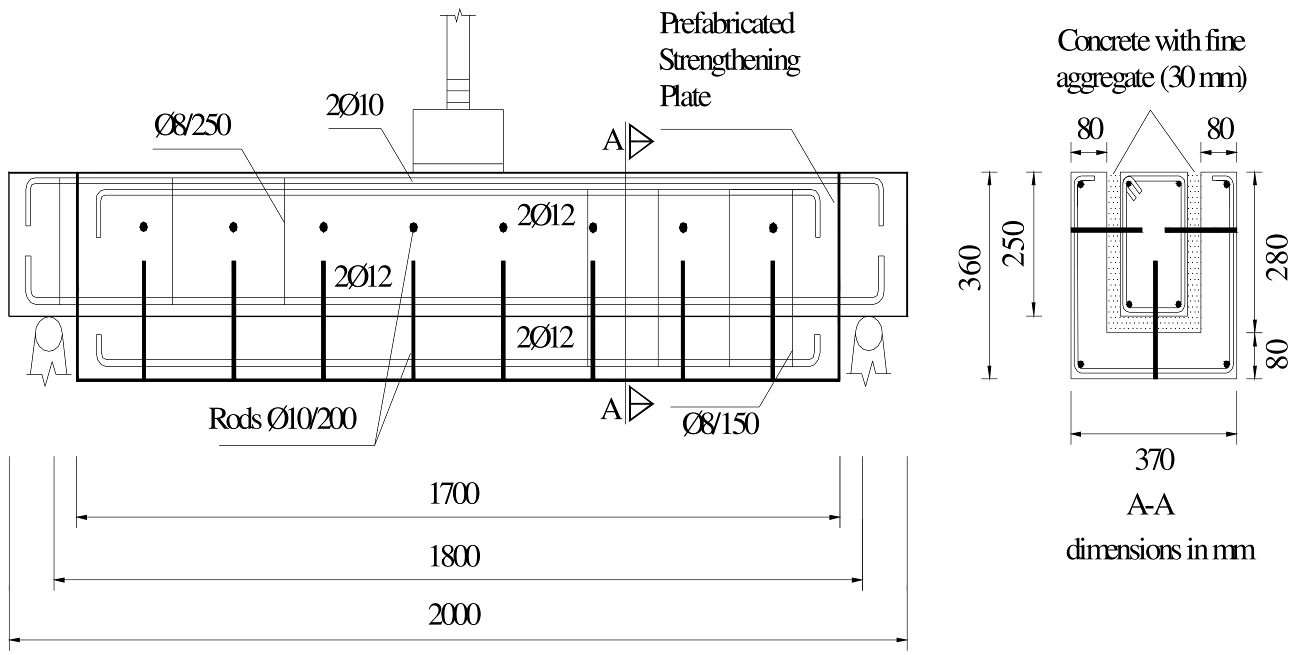

Figure 4. The strengthening with "c" plates of the second type beams named "B".

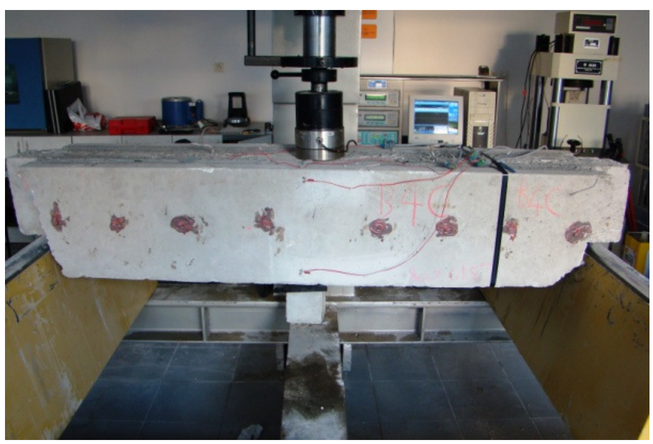

Figure 5. The loading of the strengthened beam.

$$M_r = A_s f_s \left(d - \frac{A_s f_s}{0.85 f_c b_w} \right) \quad (2)$$

$$M_d = \frac{P_F L_n}{4} + \frac{P_G L_n^2}{8} \quad (3)$$

Where, A_s is the cross-sectional area of tensile reinforcement; f_s yield strength in tensile reinforcement; f_c compression strength of concrete cube specimens. In the strengthened beams, A_s is the total tension area of the beam and the strengthening plate. k_1 is the ratio of the depth of the equivalent rectangular stress block to the depth of the neutral axis and expressed in ACI 318 and TS500 (2002). M_r is the moment carrying capacity; M_d is the moment due to loads. P_F, P_G, L_n are the theoretical failure load, uniform distributed load due to weight of beam and clear span of beam, respectively.

EXPERIMENTAL AND THEORETICAL RESULTS

The beams A1, A2, A3, B1, B2, and B3 were loaded until

Table 1. Material, steel, cross-section properties of elements.

Elements	Tension bars	Stirrups (mm)	Depth (mm)	Width (mm)	σ_{Cube} (MPa)
A1	2Ø12	Ø8/150	250	150	19.68
a1	2Ø12	Ø8/100	80	150	22.19
A1a	4Ø12	-	330	150	
A2	2Ø12	Ø8/150	250	150	14.17
b1	2Ø12	Ø8/100	120	150	15.53
A2b1	4Ø12	-	370	150	
A3	2Ø12	Ø8/150	250	150	15.53
b2	2Ø12	Ø8/100	120	150	17.14
A3b2	4Ø12	-	370	150	
B1	2Ø12	Ø8/250	250	150	17.65
c1	2Ø12	Ø8/150	80	370	19.69
B1c1	4Ø12	-	360*	370	
B2	2Ø12	Ø8/250	250	150	16.13
c2	2Ø12	Ø8/150	80	370	15.77
B2c2	4Ø12	-	360*	370	
B3	2Ø12	Ø8/250	250	150	17.15
c3	2Ø12	Ø8/150	80	370	18.30
B3c3	4Ø12	-	360*	370	

*30 mm concrete with fine aggregate.

Table 2. Properties of reinforcements.

Bar size (mm)	Young's modulus E_s (MPa)	Yield strength (MPa) f_s	Ultimate strength (MPa)
8	210000	430	670
10	210000	425	660
12	210000	427	665

Table 3. Technical properties of HILTI HIT-RE 500.

Bond strength ASTM C882-911	12,4 MPa (7 day cure)
Compressive strength ASTM D-695-961	82,7 MPa
Compressive modules ASTM D-695-961	1493 MPa
Tensile strength 7 day ASTM D-638-97	43,5 MPa
Base materials	Concrete
Anchor type	Chemical anchor
Material composition	Epoxy-adhesive
Base material temperature-range	-5-40℃

flexural cracks started. These cracks were repaired with epoxy called "Hilti". The strengthened beams were loaded until they failed. The failure loads and increase in load carrying capacities were given in Tables 4 and 5.

The present experimental results indicated that the load-displacement curves of the beams (Figures 8 and 9) can be idealized by a bi-linear curve (Figure 10). The displacement ductility factor μ_Δ, which is defined as the ratio between the displacement at peak load Δ_u and the notional yield displacement Δ_y is adopted to measure the

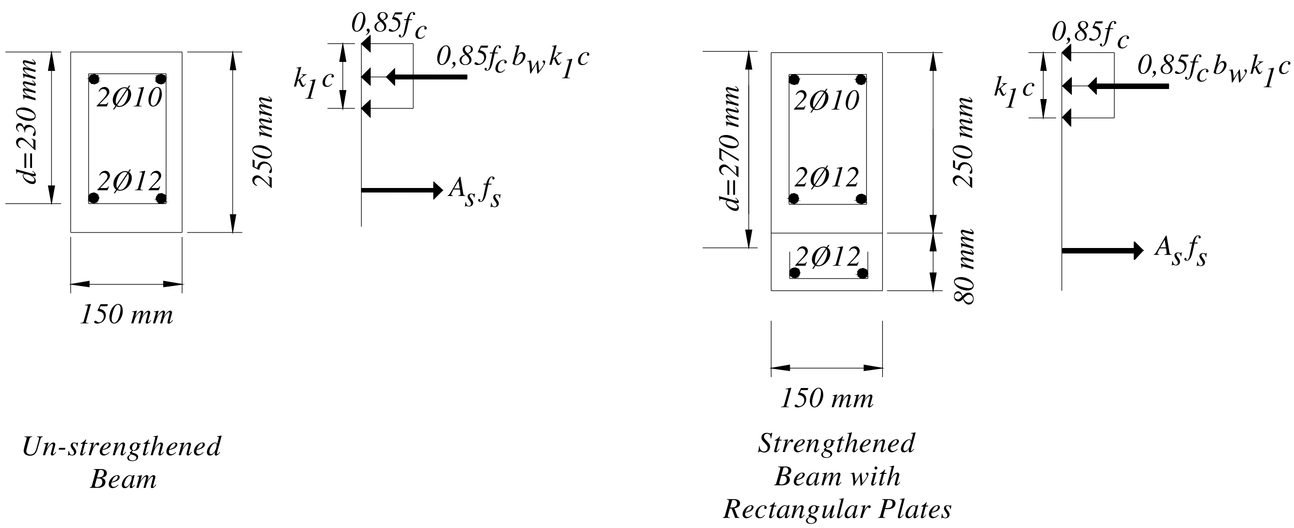

Figure 6. Finding of theoretical failure load for un-strengthened and strengthened beam with rectangular cross-sectional plates.

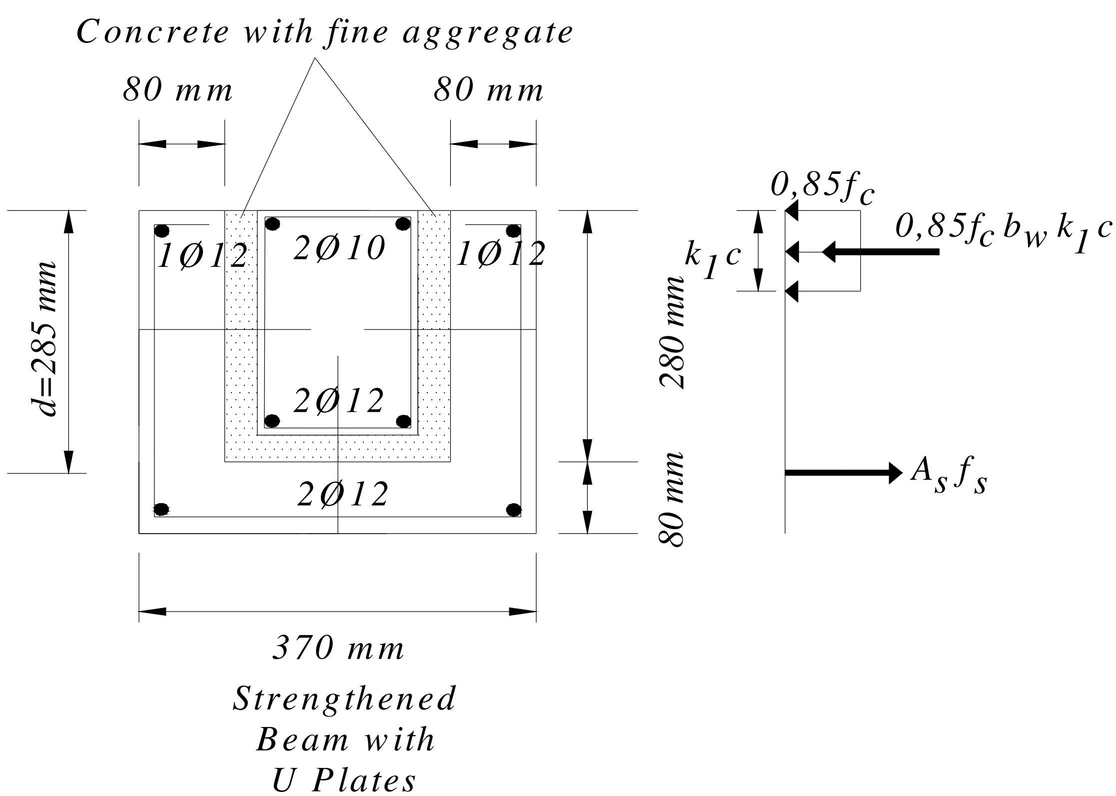

Figure 7. Finding of theoretical failure load for un-strengthened and strengthened beam with U cross-sectional plates.

ductility performance of the strengthened beams (Su et al., 2010). The displacement ductility factors of all beams were calculated using the above definitions and the results were shown in Tables 6 and 7. Substantial post-

Table 4. Failure Loads for Beams (with Rectangular Cross-section).

Element	Experimental load capacity (kN)	Theoretical load capacity (kN)	Increase in experimental load capacity due to strengthening (%)	Failure type
A1	47.34	42.84	48	Bending
A1a1	70.14	93.37		Bending
A2	45.10	40.94	30	Bending
A2b1	58.60	85.80		Failure of support
A3	47.50	41.54	46	Bending
A3b2	69.40	90.49		Bending

Table 5. Failure Loads for Beams (with U Cross-section).

Element	Experimental load capacity (kN)	Theoretical load capacity (kN)	Increase in load capacity due to strengthening (%)	Failure type
B1	48.10	42.28	74	Bending
B1c1	83.88	110.50		Failure of Support
B2	43.10	41.77	78	Bending
B2c2	76.59	107.73		Failure of Support
B3	45.30	42.12	77	Bending
B3c3	80.10	102.29		Failure of Support

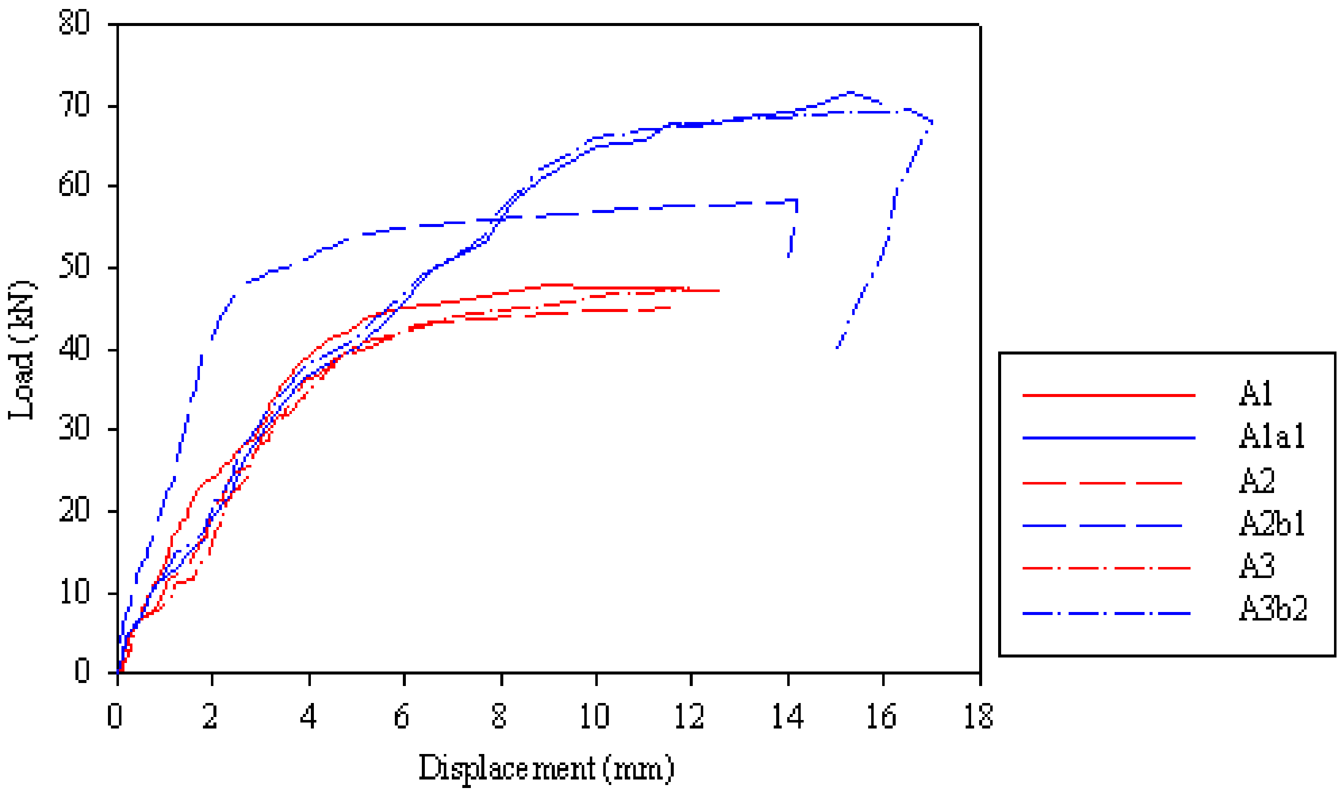

Figure 8. Experimental load–displacement curves for un-strengthened and strengthened beams with plates having rectangular cross-section.

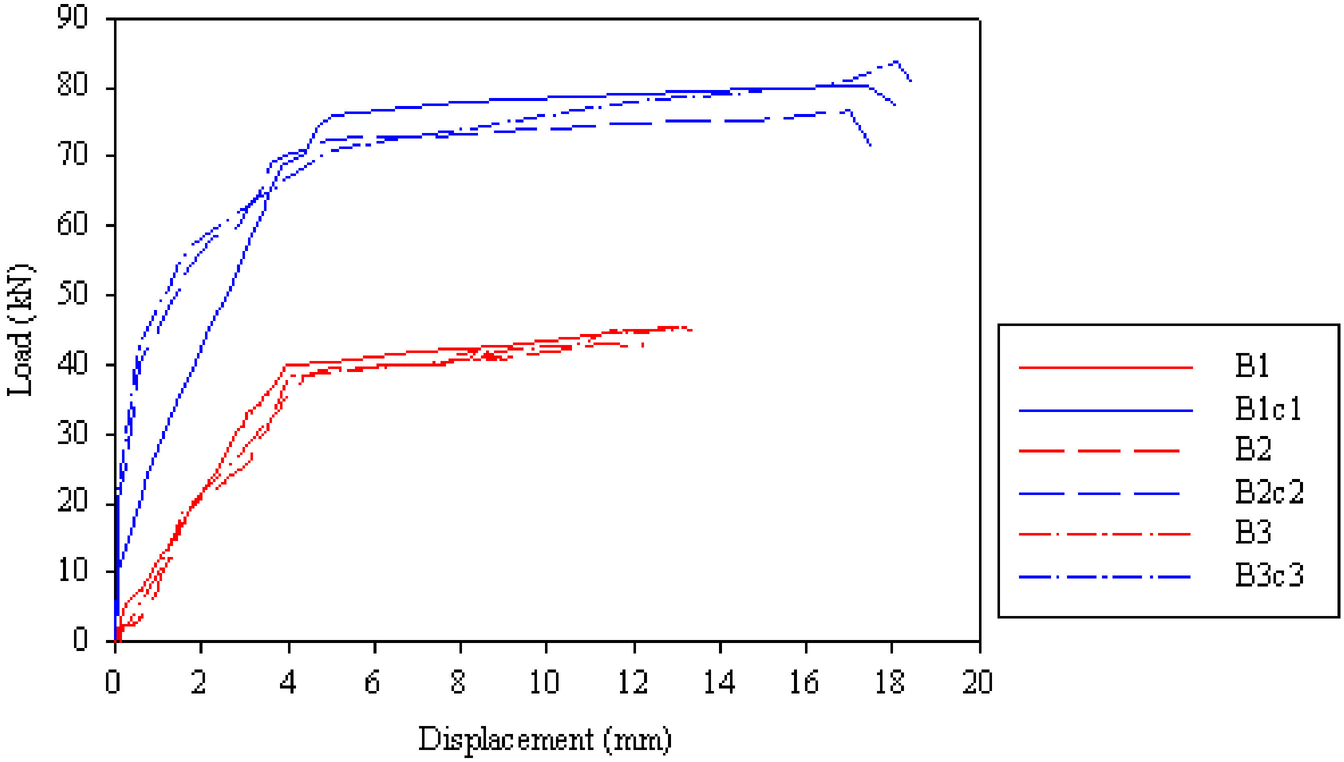

Figure 9. Experimental load–displacement curves for un-strengthened and strengthened beams with plates having U cross-section.

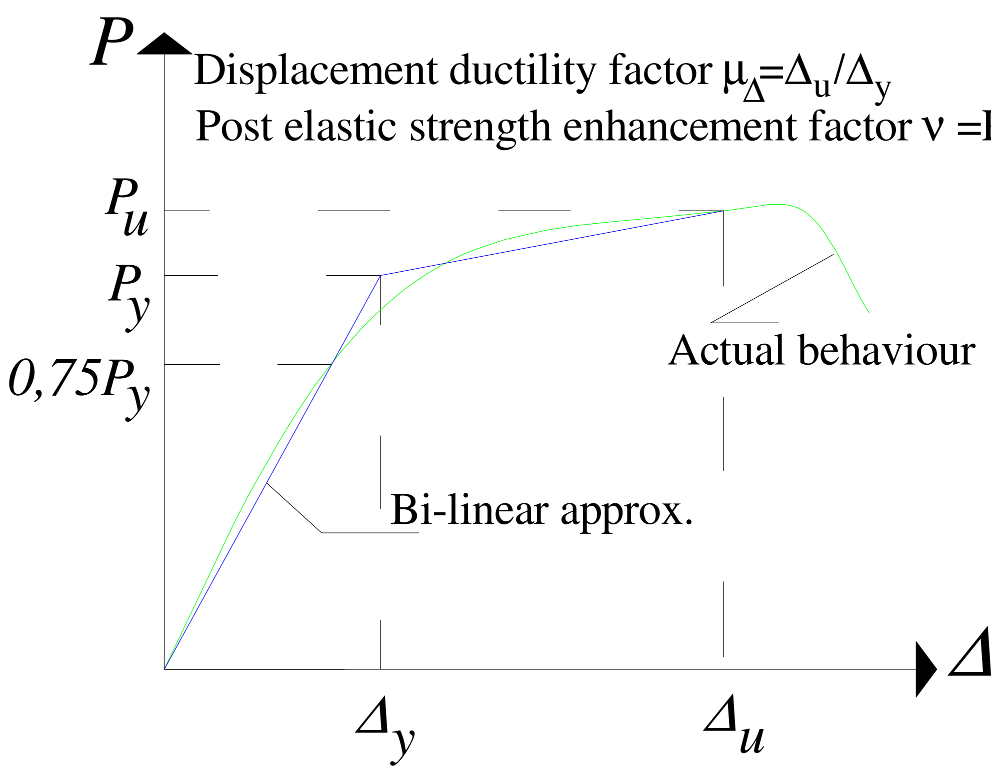

Figure 10. Definitions of displacement ductility factor and post-elastic strength enhancement factor.

Table 6. Comparison of displacement ductility factors and post-elastic strength enhancement factors.

Specimen	Δ_y (mm)	Δ_u (mm)	μ	P_y (kN)	P_u(kN)	v
A1a1	7.32	16.00	2.186	61.40	70.14	1.142
A2b1	3.04	14.20	4.670	47.70	58.60	1.229
A3b2	7.03	16.50	2.347	59.13	69.40	1.174

μ = displacement ductility, **v =** the post-elastic strength enhancement factor.

Table 7. Comparison of displacement ductility factors and post-elastic strength enhancement factors.

Specimen	Δ_y (mm)	Δ_u (mm)	μ	P_y (kN)	P_u(kN)	v
B1c1	5.11	17.40	3.41	75.88	80.10	1.06
B2c2	4.18	17.00	4.07	70.57	76.59	1.09
B3c3	4.50	18.10	4.02	70.01	83.88	1.20

μ =displacement ductility, **v=** the post-elastic strength enhancement factor.

elastic strength enhancement can be found in Figures 8 and 9. The post-elastic strength enhancement factor v is defined as the ratio between the peak strength, P_u and the yield strength, P_y, (Figure 10) (Su et al., 2010). Tables 6 and 7, shows the post-elastic strength enhancement factors of the beams.

Conclusions

There are several strengthening methods found in the literatures which use FRP plates or steel plates. But, corrosion is an important problem for steel plates. Although, FRP plates are safe and light in weight, fire and freeze-thaw are important problems for them. Moreover, in strengthening with FRP and steel plates, the structure does not get extra strength against lateral loads. Therefore a new strengthening method for structural beams is proposed in this study.

In this method, the lateral load carrying capacity increases since the depth of the beams increase. In addition, the moment and shear capacities of beams are increased. Strengthening with rectangular cross-sectional plates, the load carrying capacity of the beams increased to 41% and those strengthened with U cross-sectional plates increased to 76%.

Since the behavior of epoxy and anchorage rods are not taken into account in equations, experimental and theoretical results of strengthened beams are incompatible. It is more compatible for un-strengthened beams according to others.

The post-elastic strength enhancement and displacement ductility are identified as two important structural performance criteria for structures predominantly subjected to gravity loads. These two criteria were greatly influenced by the prefabricated strengthening plates. It was observed that sufficient ductility and strength enhancement could be achieved by the rectangular and U cross-sectional plates.

Depending on the reasons mentioned above it can be said that the strengthening method examined both experimentally and numerically is practical, reliable and economic. Since the strengthening plate is made of the same material as the beams, it is more aesthetic and economic. The strengthening method proposed is a good alternative to strengthening with FRP and steel plates. More experimental and theoretical studies are recommended with reverse cycling loading for the better determination behavior of strengthened beams with prefabricated RC plates.

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