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# Strengthening and Rehabilitation of RC Beams with FRP Overlays under Combined Shear and Torsion

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ABSTRACT: This paper deals with evaluating the rehabilitation convenience of a damaged RC beam under the combined shear-torsion effect and retrieving its shear-torsion capacity by using FRP rolled strips. To this end, 9 specimens with 2.85 m lengths and clamped-clamped boundary conditions were made and tested under combined shear and torsion up to fracture (from zero loading eccentricity, corresponding to pure shear, to infinite eccentricity, due to pure torsion). Five of the specimens were ordinary (control) specimens considered as reference and four of them were strengthened with FRP strips from the beginning. Also, four of the ordinary specimens were rehabilitated after fracture by rubbing cement mortar on the cracked faces, then strengthened and tested like other specimens. Results indicated that rehabilitating and strengthening the beam will not only retrieve the initial shear-torsion capacity, but also increase the ultimate capacity up to 60 %. The increased capacity for the specimens strengthened from the beginning was 97%.

*Keywords: Rehabilitation; Strengthen(ed); RC beam; FRP composite; Shear-torsion.*

## 1 INTRODUCTION

Strengthening RC structures has received considerable work all over the world at least for two decades. In the early 90s, the principal intent for strengthening RC members was to improve their defects happening due to promotion in design codes and necessity to increase safety factors. Moreover, strengthening was needed when the function of a structural section was changed and dictated that the capacity of some elements be increased [1-3].

In almost all studies in this field, RC members are strengthened from the beginning and their behavior has been compared to that of unstrengthened specimens. However, in many cases of practice, the behavior of RC members must be evaluated after the structure has been loaded and, at least, some of the members have been damaged to a certain extent (usu. due to earthquake), and therefore, may need to be rehabilitated for further use.

Structural members can be strengthened in several ways including the use of concrete or steel jackets and FRP strips. In the latter case, the majority of works reported in the literature correspond to strengthening members against thrust, flexure, and shear [4], and a few works are about strengthening against torsion [5-7]. The results of some works have been used as benchmark in deriving the formulas included in design codes such as ACI 440-2R [8] and FIB [9].

Metal sheets were used to rehabilitate an RC beam against torsion by Kozonis [10]. His results demonstrated that the torsional capacity of the beam after rehabilitation is 3-35 percent more than that of the ordinary specimen which has not been strengthened up to fracture. Three bridges were strengthened by Hrick et al by injecting epoxy resin inside cracks [11]. The first one was strengthened against flexure, the second one was strengthened for amending shear-induced cracks near the supports, and the last one was strengthened against shrinkage cracks. All bridges were found to retrieve their initial load bearing capacities after rehabilitation.

Five small-scale columns were reciprocally tested under axial and lateral loads up to initial cracking by Nasrollahzadeh and Meguro [12]. The cracked columns were then rehabilitated with prestressed FRP belts and loaded again. Results revealed that rehabilitated specimens had a shear capacity with the same value as that of initial (undamaged) specimens. Moreover, the rehabilitated members could undergo larger lateral deflections.

Six full-scale beams were tested up to 90 percent of the ultimate (fracture) load by Bhikshma et al [13]. The damaged beams were then rehabilitated by injecting a number of epoxy types and reloaded. The flexural strength of specimens was increased by 15 percent.

Two ordinary beams were loaded up to initial cracking by Obaidat [14]. The cracked beams were then unloaded and strengthened with CFRP strips. The strengthened specimen's load bearing capacity was increased by 23 percent.

Four beam-to-strong column connections (not designed according to seismic design criteria) were tested under hysteretic loading of a strict earthquake by Li and Pan [15]. The damaged connections were then strengthened with FRP and reloaded. The load bearing capacity of the strengthened connection was even more than that of the ordinary one.

To the best of the authors' knowledge, research work on strengthening with FRP against combined shear and torsion is still meager [16]. Even in the present works, as in Ref. [16], the specimens have been strengthened from the beginning, not after initial damage. Thus, the present research deals with 9 RC beams under combined shear and torsion, 5 of which were ordinary and the rest were strengthened with FRP strips. Four of the ordinary specimens were unloaded after fracture, then rehabilitated by rubbing cement mortar on the cracked surface, and finally strengthened similarly with FRP and underwent reloading. Each beam was put under a complete range of load eccentricities, from pure shear (zero eccentricity) to pure torsion (infinite eccentricity).

## 2 TEST PROCEDURE

### 2.1 Fixed-support assemblage

In the present research, the support conditions were clamped-clamped because of the special characteristics of the loading apparatus. The ends were clamped against bending and torsion, and the eccentric load was applied at the middle (and the centric load was applied as pure shear). The scheme of the internal forces of the apparatus is shown in Figure 1. A metal belt with a 250 *mm* length was used around the middle part to properly exert the eccentric load, and each specimen (including the five reference specimens, the four strengthened, and the four rehabilitated specimens) was tested up to fracture with a specific eccentricity, using displacement-controlled loading. The metal belt was unfastened after loading.

In order to make a flexurally-clamped support, an *H*-shaped metal deck, constrained at the top and bottom of the beam, was placed at each end as shown in Figure 2a. Each deck had a 2 *m* length and the loading axis was constantly placed at the middle of the assemblage, and the beam was seated on a different point of the lower H-shaped deck in each eccentricity. The top and bottom decks were connected from two sides, one with stiffeners and the other with bolts which are screwed after the beam had been placed on the eccentricity place. Also, in order to forestall any small flexural rotation on each end, grout was poured between the bottom of the section and the lower deck, and between the top of the section and the upper deck. In order to make the support torsionally-clamped, two L-shaped elements, stiffened by triangular plates, were connected to the decks on the top and bottom of the section as shown in Figure 2b. Also, in order to forestall any small torsional rotation on each end, grout was poured between the beam sides and the stiffened elements.

When pure torsion was needed, an inside support was placed at the middle, acting as a compensator for torsion preventing shear and bending. This inside support was, as portrayed in Figure 3, a two-hinged rod carrying the whole shear force exerted by the hydraulic pump. For assurance of the true behavior of this support, foam plates were placed at the top and bottom of the beam section at the two ends before pouring grout. Thus, the end supports did not have contribution in carrying the imparted shear force, and the whole force was transferred to the inside support. The load cell placed under this rod over the metal belt indicated that the load exerted on the lever connected to the belt was fully transferred to the rod. Thus, bending and shear won't be created in the structure.

To become assured of the correct behavior of the supports, displacement gauges were used. To measure the rotation at each end of the beam, two gauges were placed along the support such that the rotation be determined from the difference of the values measured by the two gauges, divided by their distance. This calculation was done for all specimens and it was figured out that there exists enough flexural rigidity in both supports. Also, for confidence about torsional rigidity of the beam sides, displacement gauges were placed at the two sides to measure the lateral displacement. From these measurements it was also found out that the torsional support is almost fully rigid [17].

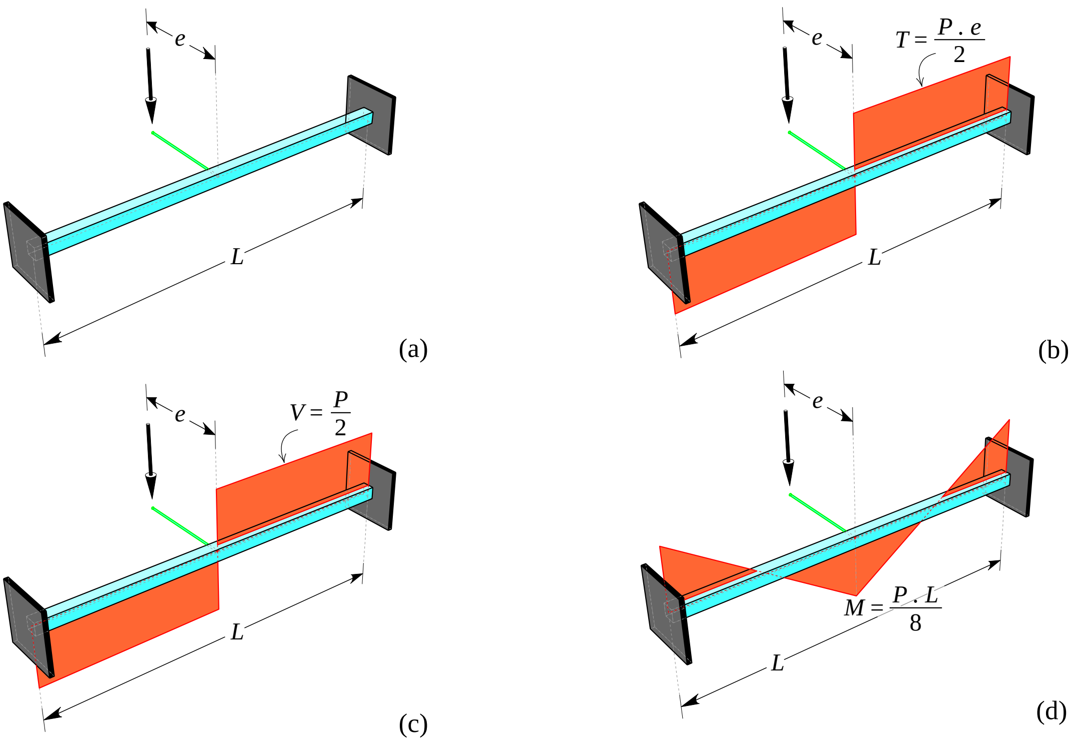
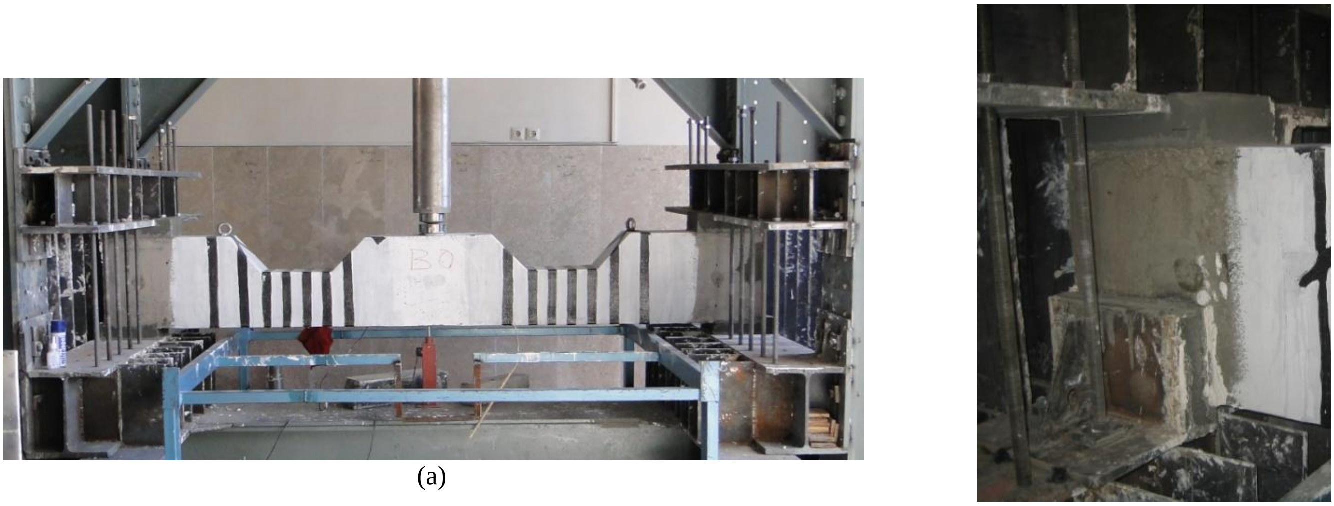



Figure 1. Loading and internal forces in the test beams; (a) Loading scheme, (b) Torsion diagram, (c) Shear force diagram, (d) Flexural moment diagram.



(a)

(b)

Figure 2. (a) Flexural rigid support, (b) torsional support

## 2.2 Test specimens

Because of the restrictions in the test apparatus, it was inconvenient, however possible, to make a multi-bay beam. Instead, the nonprismatic assemblage shown in Figure 4 was prepared. This lies behind the fact that, on the basis of the designed supporting system, the zone with negligible bending moment stands in the two end quarters of the length, i.e. between the contraflexure points and the supports. For this reason, the beam cross section and its hoops were reduced in the end quarters to concentrate the shear-torsion fracture zone to those regions. Otherwise, the ultimate load, and thus the moment in the middle and the ends would have increased, and this would have intertwined the flexural and shear-torsional behaviors in fracture. However, the beam ends had to have larger cross sections to provide sufficient rigidity at the clamped supports.

On the other hand, the longitudinal and transverse (hoop) reinforcements were increased in zones with high bending moments (to prevent flexural or, less -- - probably, shear-torsional fracture from happening in those regions) and decreased to the minimum requirement stated in ACI 318-08 [18] in the reduced cross sections (to reassure that shear-torsional fracture occurs in these cross sections). Moreover, the longitudinal and transverse reinforcing bars in the flexural zone were made of steel with a 400 *MPa* tensile strength and had 16 and 8 *mm* diameters, respectively. However, the hoops used in the reduced sections (i.e. the test regions) had 4 *mm* diameter and

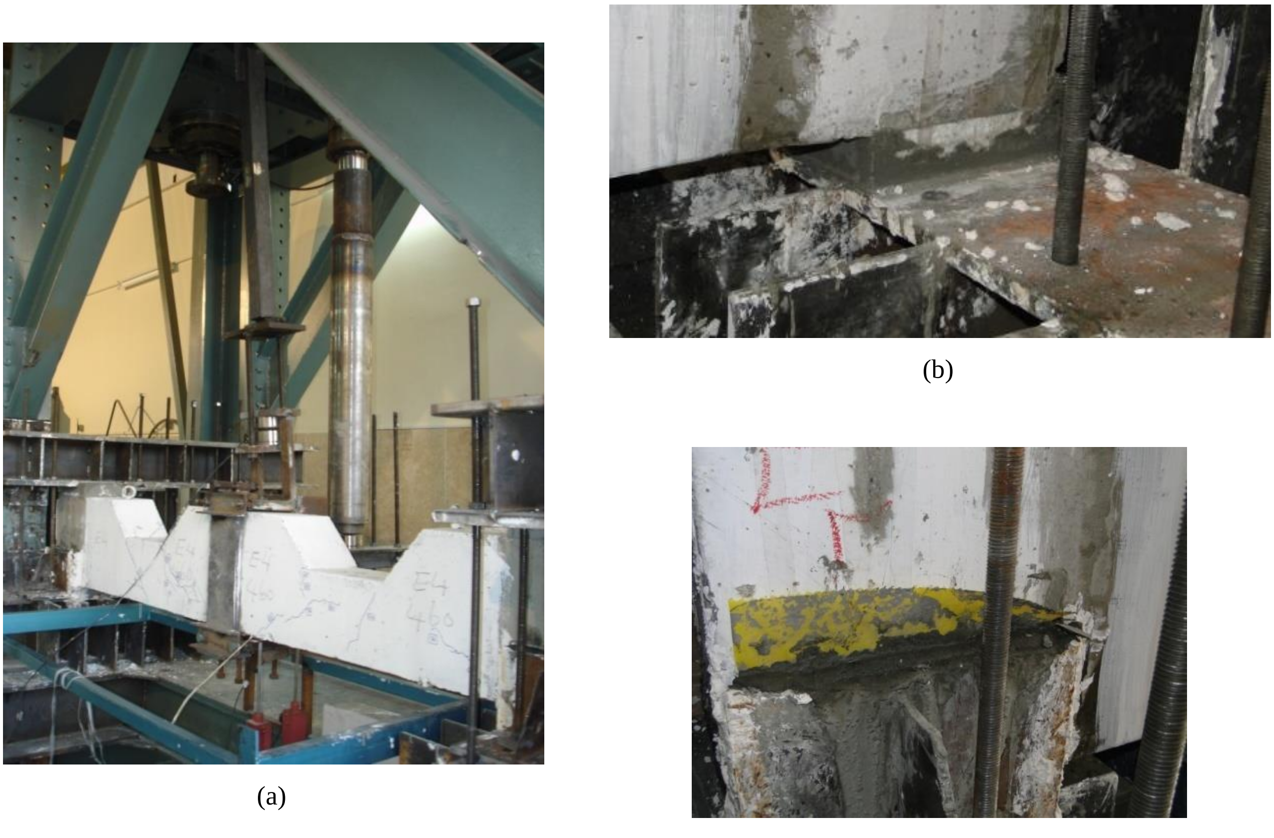


Figure 3. Pure torsion test setup; (a) vertical shear compensating member (b) polystyrene plate between the bottom of beam and lower grout; (c) plastic thin film between side of beam section and side grout

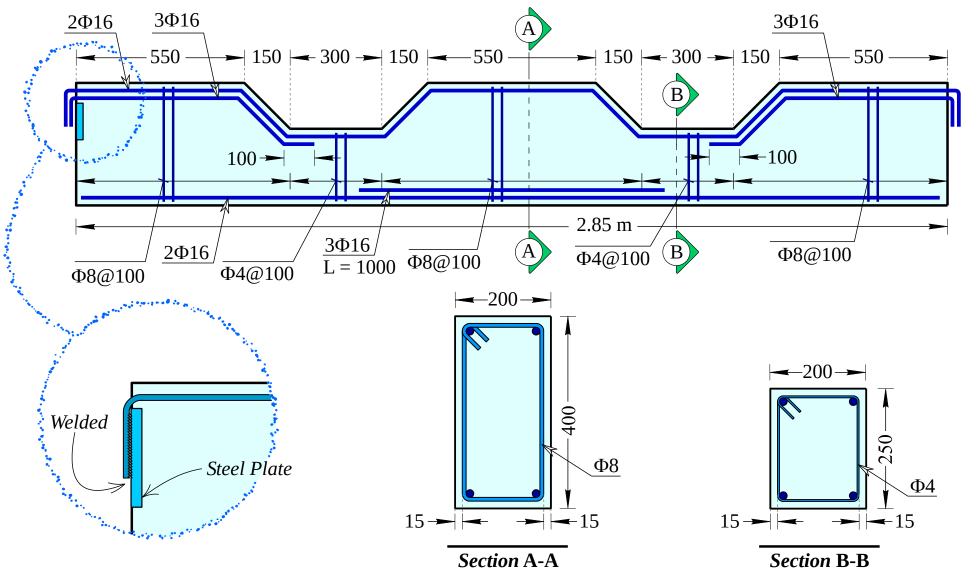



Figure 4. Specimens dimension and reinforcement (all dimensions in mm)

had 240 *MPa* tensile strength. The concrete used in all specimens had a 35 *MPa* compressive strength. Finally, to be confident that the bars have been anchored sufficiently, steel plates with an 8 *mm* thickness were used as mechanical anchors, which were welded to the hooked bar ends and placed in the cast before concrete was poured in place.

Table 1. Specimens Properties

| Group | Test No. | Specimen name | Ecc. (mm) |
|---|---|---|---|
| 1. Reference beams | 1 | E0 | 0 |
| | 2 | E1 | 290 |
| | 3 | E2 | 470 |
| | 4 | E3 | 616 |
| | 5 | E4 | ∞ |
| 2. Strengthened beams | 6 | B0 | 0 |
| | 7 | B2 | 470 |
| | 8 | B3 | 616 |
| | 9 | B4 | ∞ |
| 3. Rehabilitated beams | 10 | E0R | 0 |
| | 11 | E1R | 290 |
| | 12 | E2R | 470 |
| | 13 | E4R | ∞ |

Table 1 includes the specimens' names, types (reference, strengthened, and rehabilitated specimens), and each specimen's load eccentricity, ranging from zero (pure shear) to infinity (pure torsion).

Group *B* specimens were strengthened with CFRP rolled strips from the beginning, as shown in Figure 5. The strips had 40 *mm* widths and were placed 85 *mm* apart (the center-to-center distance). Group *E* specimens were firstly made ordinarily (unstrengthened) and loaded up to fracture, and then were rehabilitated (with cement mortar rubbed on the cracked surfaces), then strengthened (with FRP), and finally reloaded exactly like other strengthened specimens (group *B* specimens). Due to its low workability, it was impossible to inject cement mortar into the cracks. In some specimens, the rehabilitated cracks were very wide and intense, as shown in Figure 6. After rubbing mortar on the surface, it was abraded with a grinding machine to be appropriately prepared for sticking FRP strips.

## 3 RESULS AND DISCUSSION

In each experiment, several cases including the shape of cracks and their propagation trend, the load corresponding to the initial crack, the FRP debonding load, and the ultimate load (load bearing capacity) were obtained and analyzed, which will be discussed in the sequel.

### 3.1 Cracking pattern

All cracks were observed to have an inclined pattern due to the purely shear or shear-torsional behavior of specimens. Moreover, in all specimens under shear-torsional or purely torsional loading, face 2 (shown in Figure 7) was cracked at first. Cracking was then followed on faces 3, 4, and 1, or 3, 1, and 4. However, in purely shear loading, cracking occurred on faces 2 and 4 simultaneously. All the observed cracking patterns, including the spiral-like (torsional), diagonal (shear), and intermediate (shear-torsional) cracks conformed well to the contents of the existent literature [19, 20]. Figure 8 shows examples of cracking on the fracture threshold, which pertain to *E2*, *B2*, and *E2R* specimens (undergoing a 470 *mm* eccentricity).

All the same, in rehabilitated specimens, cracking was initiated and developed up to fracture on face 4. It is noteworthy that the placing of these specimens was done such that the twisting direction of the specimen be exactly the same as that in the ordinary specimen. Moreover, some sporadic cracks were also observed on face 2. Also, the rehabilitated specimens were observed to deform largely on the fracture threshold, such that a rigid-body motion was seen at the cracked zone, around the beam horizontal axis.

Finally, in all strengthened specimens, either strengthened from the beginning or strengthened after rehabilitation, cracks were more dispersed on different faces than those in ordinary specimens.

In ordinary specimens, the cracks' angles ranged between 34 and 40 degrees. In strengthened specimens, the cracks' angles approached 45 degrees. Moreover, the major cracks' widths in strengthened specimens (occurring on face 2) were decreased to almost 20 percent of those in ordinary specimens.

### 3.2 Cracking, ultimate, and debonding loads

Table 2 includes the cracking and ultimate loads of all specimens as well as the debonding load for each strengthened specimen. This table reveals that the ultimate (capacity) load in specimens strengthened from the beginning is almost 97 percent more than that of the reference specimen while it is almost 59 percent more in rehabilitated specimens. Namely, rehabilitated and then strengthened specimens not only have retrieved their initial (ordinary) load bearing capacity, but also have reached almost 1.6 as much capacity after they have been strengthened. The reason can be explained such that, as stated in building codes containing FRP design requirements, the net shear-torsional and purely shear capacities of a cross section consists of three parts: the part provided by concrete, reinforcement, and FRP. In order to obtain the part of purely shear capacity provided by FRP, one can subtract *E0*'s capacity from *B0*'s capacity, which will be obtained 110 *kN*. Thus, in *E0R*, with a 177 *kN* capacity, the remaining 67 *kN* capacity must have been provided by the uncracked zones, the interlocking of ingredients, and the dowel action induced by longitudinal bars and a very little of this portion has been undertaken by the cracked concrete. This lies on the fact that, as previous studies have demonstrated, the post-cracking concrete shear transfer coefficient, i.e. the fraction of the overall cross section shear capacity transferred by concrete, is around 10 percent [21], which will be 13 *kN* for *E0*. Thus, the majority of the 67 *kN* capacity must have been provided by other factors as stated above. The same logic can be extended to shear-torsional loading. However, in purely torsional loading, since the longitudinal reinforcement in the test zone (i.e. the reduced section) is rather large, these bars have contributed to torsional load bearing and have hence increased the cracking and ultimate loads (by 68 percent). Furthermore, the increased value of cracking load in rehabilitated specimens is negative. Namely, rehabilitated specimens crack with smaller loads than do ordinary specimens. This happens, obviously enough, due to cracking in the reference specimen, which causes concrete to strictly lose advantage.

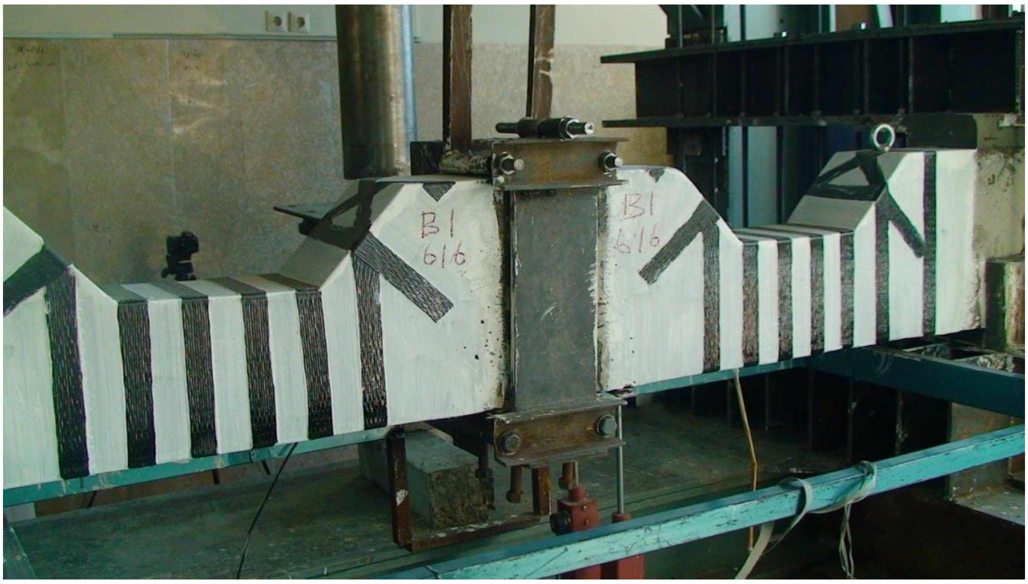


Figure 5. Strengthening of specimens

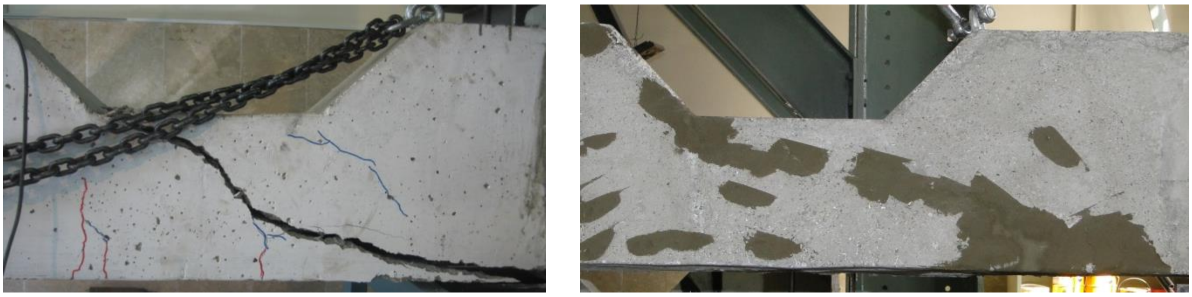


Figure 6. Cracking of E0 specimen and its repairing to prepare E0R specimen

It can also be obtained from Table 2 that the ultimate-to-cracking load ratio is (averaged to) 1.7 for ordinary, 2.4 for strengthened, and 4 for rehabilitated specimens. The last one is larger because of the significant role of FRP strips in retrieving the shear-torsional load bearing capacity for specimens in which the torsional capacity provided by ordinary concrete before cracking has been very small. Finally, FRP debonding loads and their division by the cracking and ultimate loads are included in Table 2. In all strengthened specimens, vertical cracks were observed after debonding between the concrete and glue. Also, debonding was extended by increasing the load, but FRP strips were torn in all specimens after debonding. The variation of the debonding-to-ultimate load ratio in specimens under combined shear and torsion is similar to that of the cracking load in that it decreases with load eccentricity.

Table 2. Experimental results

| Group | Specimen | Cracking load (kN) | Ultimate load (kN) | Increase in cracking load (%) | Increase in ultimate load (%) | Debonding load | D/Ult.* | D/Cr.** |
|---|---|---|---|---|---|---|---|---|
| 1 | E0 | 100.0 | 134.0 | --- | --- | --- | --- | --- |
| | E1 | 38.0 | 49.2 | --- | --- | --- | --- | --- |
| | E2 | 21.0 | 33.7 | --- | --- | --- | --- | --- |
| | E3 | 18.0 | 29.0 | --- | --- | --- | --- | --- |
| | E4 | 20.0 | 55.0 | --- | --- | --- | --- | --- |
| 2 | B0 | 133.0 | 246.0 | 33.0 | 83.6 | 165 | 0.67 | 1.24 |
| | B2 | 38.0 | 72.8 | 80.9 | 116.0 | 40.7 | 0.56 | 1.07 |
| | B3 | 25.0 | 57.2 | 38.9 | 97.2 | 31.9 | 0.56 | 1.28 |
| | B4 | 30.0 | 104.4 | 50.0 | 89.8 | 41.2 | 0.39 | 1.37 |
| 3 | E0R | 44.3 | 177.1 | -55.7 | 32.2 | 103.1 | 0.58 | 2.33 |
| | E1R | 18.3 | 82.8 | -51.8 | 68.3 | 65.7 | 0.79 | 3.59 |
| | E2R | 15.0 | 62.6 | -28.6 | 85.8 | 25 | 0.40 | 1.67 |
| | E4R | 24.5 | 81.9 | 22.5 | 48.9 | 39.2 | 0.48 | 1.60 |

* D/Ult.: Debonding load to ultimate load ratio
** D/Cr.: Debonding load to cracking load ratio

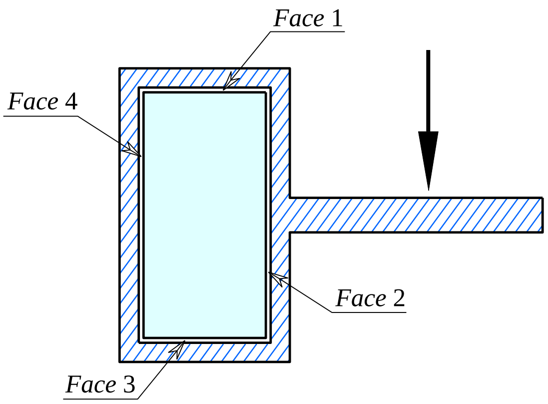


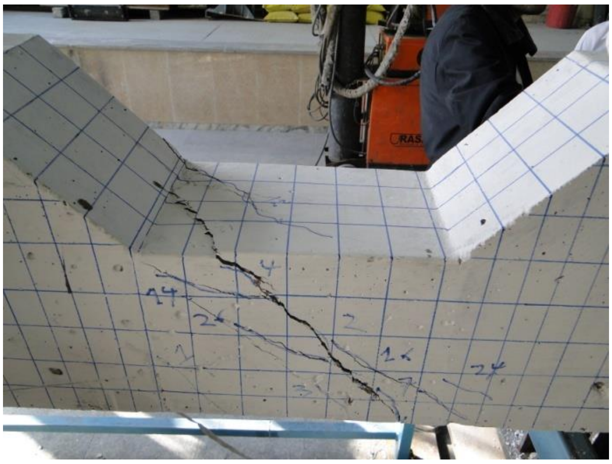

Figure 7. Numbering of beams section for describing the crack pattern

## 3.3 Curves of behavior

The twisting rotation was measured by using two LVDTs on the middle cross section width ends, and dividing the difference of the measured digits by the cross section width. Due to the structural weakness induced by reducing the section at the proximity of the contraflexure points, fracture occurred in the reduced zone in all specimens, and the bigger section had only rigid movement. Hence, the twisting torque-vs.-twisting rotation curves for all specimens depend directly on the behavior of the reduced section. The curves pertaining to the bigger section are thus different only in a rigid-body rotation. All curves have been depicted in Figure 9. In all curves, except 9c, there exist curves corresponding to the ordinary, strengthened, and rehabilitated specimens. These curves demonstrate that the initial stiffness of strengthened specimens (those strengthened from the beginning) has been increased, as compared to ordinary (reference) specimens. However, the initial stiffness of rehabilitated specimens has decreased. Moreover, the energy absorption, often called ductility, defined as the area beneath the load-deflection (here: torque-rotation) curve, in rehabilitated specimens is less than that in strengthened specimens. However, the load bearing capacity of these specimens is much higher than that of ordinary specimens.

## 4 CONCLUDING REMARKS

This research paper aims at studying the convenience to retrieve the shear-torsional capacity of damaged RC beams with FRP strips. To this end, 9 RC beams were designed and made, 5 of which were ordinary (reference) and 4 were strengthened with CFRP rolled strip. Each strengthened specimen was tested under a specific loading eccentricity at a time, ranging from zero (pure shear) to infinity (pure torsion) up to fracture. Four of the reference specimens were rehabilitated with cement mortar and strengthened the same way as other specimens were strengthened. The beams were made clamped at each end. Results indicated that strengthened specimens' cracking and ultimate loads were 33-80 percent and 83-116 percent larger than those of ordinary specimens, respectively. The increase in the cracking and ultimate load was decreased with the load eccentricity. The increase in the cracking load in the purely torsional specimen was more than that in other eccentricities.

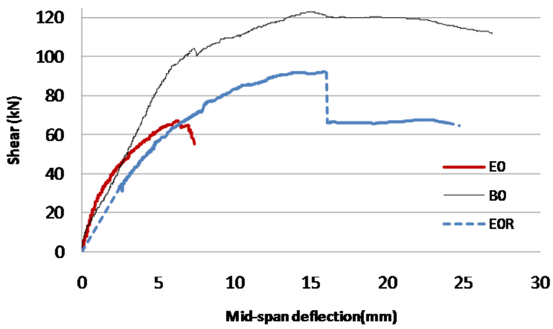


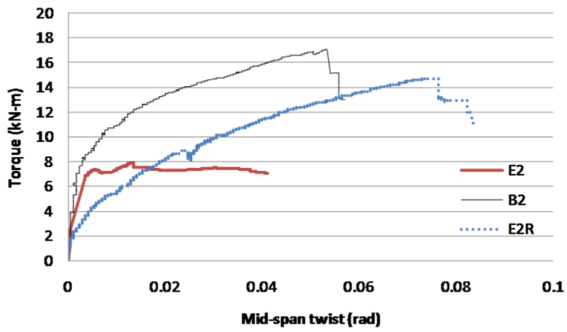
(a)

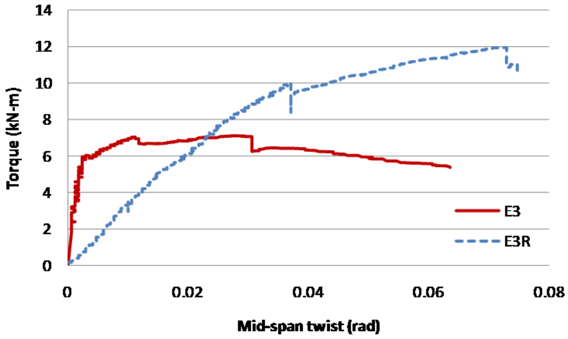
(b)

(c)

Figure 8. Cracking of face #2 for specimen; (a) E2; (b) B2; (c) E2R



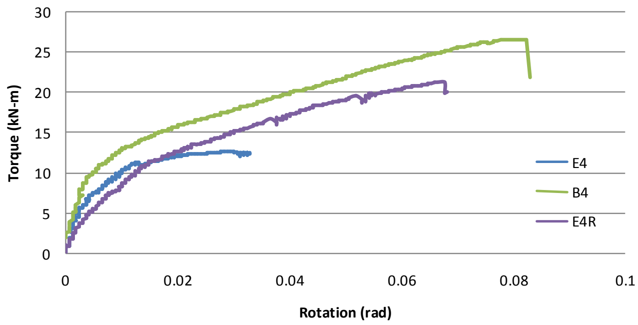




Figure 9. Experimental behavior curves

In rehabilitated specimens, the load bearing capacity faced the average of 60 percent increase. The cracking pattern in these specimens differed from others in that the initial cracks occurred on the face opposite to the face on which other specimens cracked. Also, these specimens had rigid twisting movement after initial cracking. The cracking load in these specimens decreased by 28 percent, except for the one undergoing pure torsion where the cracking load was increased by 22 percent. Likewise, all specimens under purely torsional loading had higher cracking loads than specimens with less-than-infinity load eccentricity. Finally, the torque-rotation curves plotted for these specimens proved that the shear-torsional capacity is increased whereas the ductility is decreased in comparison to reference specimens.

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