FRP REPAIR TECHNIQUES FOR R.C. BEAMS PRE-DAMAGED IN SHEAR

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KEYWORDS: Fiber reinforced polymer, Reinforced concrete beams, Retrofitting, Shear strength, Strengthening

ABSTRACT

FRP (fiber reinforced polymers) has been used for both strengthening and Repair of reinforced concrete (RC) members since the nineties. FRPs were first used in seismic retrofitting of RC columns by wrapping. FRPs were then used in the flexure strengthening of RC beams and slabs, later they were used in the shear strengthening of RC beams. Typically Carbon or glass fiber sheets externally bonded to the bottom and sides of RC beams were used for the shear strengthening of RC beams. Another technique, previously proposed by the authors, is to strengthen RC beams in shear by drilling holes through the depth of the beams and then embedding FRP rods in these holes. In this paper a comparison of these two techniques in strengthening and repairing RC beams is presented. Six beams were tested; a control beam without strengthening, two beams strengthened using externally bonded CFRP (Carbon fiber reinforced polymer) sheets and two beams strengthened using embedded CFRP rods. For each technique one specimen was preloaded beyond the formation of the first crack before strengthening while the other was not preloaded in order to study the effects of preloading. The last specimen was the control specimen which was retrofitted after being loaded to failure in shear then retested again after repair.

INTRODUCTION

Generally, reinforced concrete beams fail in either flexural or shear failure mode. In the case of flexural failure mode, the beam gives enough warning in the form of cracks and large deflection. However, brittle shear failure mode takes place in the case of beams having little amount of shear reinforcement. For this reason, codes of practice recommend that reinforced concrete beams should have enough shear reinforcement in order to ensure the occurrence of ductile flexural failure rather than a brittle shear failure [1]. Existing reinforced concrete RC structures may require strengthening for a variety of reasons. For example, it is often desirable to increase the loading to which a structure is subjected, as when a bridge must carry increased traffic or when a building must be used for purposes other than those for which it was originally designed. It may also be necessary to strengthen old RC structures as a result of new code requirements or because of damage to the structure as a result of environmental stresses.

Repairing and strengthening of reinforcement concrete beams to increase their strength against shear forces is a common work in construction society. Traditional methods are mainly used such as strengthening the concrete beams and repair to increase the resistance to shear forces. This is a major problem in the Egyptian market as a result of increasing loads due to changing the use of such buildings, poor design or weather conditions and tough environment which decrease building resistance. Therefore it's recommended to use traditional methods for beam strengthening like increasing reinforcement or section enlargement, which have the disadvantages of high cost and increased beam section.

Practically, repairing or strengthening such beams by adding internal shear reinforcement is very difficult. It was found that such strengthening may be easily achieved externally by bonding either steel plates or fiber reinforced polymers (FRP) to the beam surface using suitable epoxies. Experimental investigations found in the literature [2-14] indicated a basic difference in the mode of failure for externally strengthened beams than that in the case of beams having internal stirrups. In the case of beams reinforced with internal stirrups, the shape and position of those stirrups placed inside the concrete ensure sufficient anchorage, thus failure is controlled by the tensile strength of stirrups. However, in contrast, in the case of externally strengthened beams, the failure is always controlled by the loss of anchorage in the form of de-bonding of strengthening materials [2-13]. Different materials were used through previous experimental studies for the external strengthening and retrofitting of RC beams deficient in shear. These materials were bonded to the external surface of the beam using suitable epoxies [2-13]. These studies included the application of either traditional steel plates [3, 4] or fiber composites [5-8]. Different types of fiber composites were used such as Glass fiber and Carbon fiber.

EXPERIMENTAL STUDY

In this study, six RC beam specimens were tested. The specimens included three repaired beams; two strengthened beams and one control beam without strengthening. All specimens had a cross section of 160 mm x 300 mm, and a total length of 2.40 meters. The specimens were designed to fail in shear at one side (The weak side). For flexure reinforcement four 22 mm deformed bars arranged in two layers were used as bottom reinforcement with 3.16 % reinforcement ratio, while two 22 mm deformed bars were used as top reinforcement. The bottom and top reinforcement were used the deformed bars with a steel grade of 360/520. The shear reinforcement for the strong side consisted of 10 mm closed-type stirrups spaced at 50 mm, while the shear reinforcement for the weak side consisted of 6 mm bars with a spacing of 150 mm. Figure 1 shows the reinforcement details of the beams.

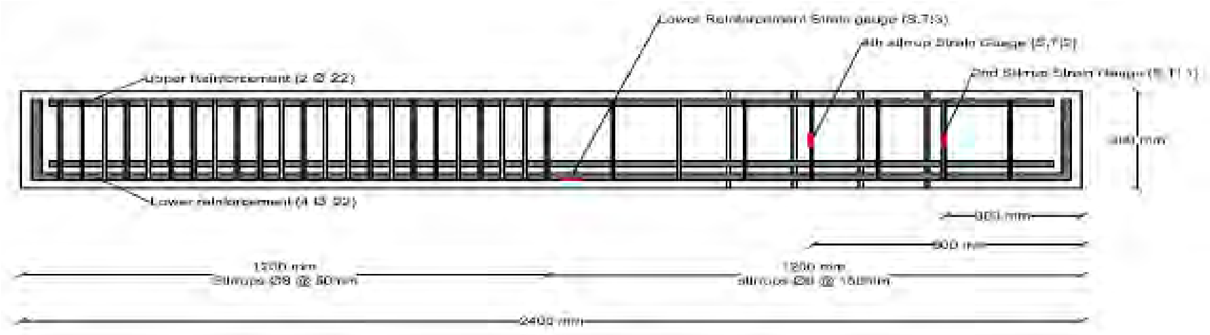

Figure 1 Reinforcement Details for all Tested RC Beams

In this research two different techniques for repairing or strengthening RC beams against shear were used. The first technique used Internally Embedded Reinforcement (I.E.R.). In this technique 12 mm CFRP bars were embedded in circular holes drilled through the depth of the beams. All the bars had a spacing of 150 mm. Figures 2, 3 show the preparation work for the repaired specimens using I.E.R. technique.

Figure 2 Drilling of holes for specimen IER

Figure 3 Installing of reinforcement in specimen IER

In the second technique CFRP sheets were externally used to repair or strengthen the beams in shear. The CFRP sheets were externally bonded (E.B.) to the sides and bottom of the beam forming a U shaped wrap around three sides of the beam. A single layer of 60 mm wide sheets with a spacing of 150 mm was used to strengthen these specimens. Figure 4 shows the strengthening of EB specimen. The configuration of the specimens was chosen so all specimens would have an equal amount of material.

Figure 4. Strengthening of specimen EB

For each technique one specimen was preloaded beyond the formation of the first crack before strengthening while the other was not preloaded in order to study the effects of preloading. The last specimen was the control specimen which was retrofitted after being loaded to failure in shear then retested again after it was repaired using the I.E.R. technique.

The preloaded specimens were given the designation "R", while the specimens that were strengthened without preloading were given the designation "S". These designations are followed by designations E.B. or I.E.R. indicating the technique used for strengthening. The numbers following indicate the load level prior to strengthening. Table 1 provides a summary of the details of the specimens used in this program.

Table 1 Specimen details

Specimen	Type of Strengthening /Repairing	Loading before repair	Dimensions of material	Spacing
Control	---	---	None	---
R-I.E.R.-100%	Internally embedded reinforcement	100% P_f^*	12 mm Bars	150 mm
R-I.E.R.-70%	Internally embedded reinforcement	70% P_f	12 mm Bars	150 mm
R-E.B-70%	Externally Bonded Sheets	70% P_f	60 mm wide sheets (One Layer)	150 mm
S-I.E.R.	Internally embedded reinforcement	0.0	12 mm Bars	150 mm
S-E.B	Externally Bonded Sheets	0.0	60 mm wide sheets (One Layer)	150 mm

*P_f : Failure Load

<u>Material properties</u>

The concrete strength for all specimens was 30 MPa based on testing 100 mm cubes, except specimen R-I.E.R-70 %, which had a concrete strength of 20 MPa. The steel bars used for the flexure reinforcement and the stirrups on the strong side had a nominal yield strength of 360 MPa, while the bars used for reinforcing the weak side had a nominal yield strength of 240 MPa. The sheets were supplied by Sika Egypt under the commercial name (Sikawrap Hex-230C). The thickness of the CFRP sheets was 0.13 mm. The tensile strength and modulus of elasticity of CFRP sheets were 3.5 and 230 GPa, respectively as provided by the product data sheet. Two-component epoxy adhesive (Sikadur 330), supplied by the same company, was mixed according to the proportions recommended by the manufacturer to bond the

CFRP sheets to the target surfaces of the tested beams. 12 mm V-Rod CFRP bars manufactured by Pultral Inc. were used for IER specimen, Sikadur 31 CF epoxy adhesive was used for fixing the internally rods inside the holes. The cracks in the control beam was patched after testing to failure using cementitios materials as shown in Figure 5 Repaired Specimen. Afterwards the beam was repaired using the I.E.R technique, and then retested.

Figure 5 Repaired Specimen

Test setup and instrumentation

All specimens were tested under four point bending. The span of the beams was 2.0 m and the distance between the loads was 0.6 m. The shear span for both sides was 0.7 m which is larger than 2.5 the depth of the beam to avoid effects of arching action. Three dial gauges were used to measure the deflection at mid-span, and both loading points. As train gauge was mounted on the second stirrups after the support at the weak side. Long strain gauges were also mounted on the concrete surface at a 45° angle. In addition strain gauges were also mounted on the second sheet and second bar after the support for specimens EB and IER respectively. Loading was applied manually through a hydraulic pump to two hydraulic jacks at increments of 10 kN, at which time readings from the dial gauges and strains were manually recorded. Figure 6 shows the loading set-up for tested beams of the tested specimen.

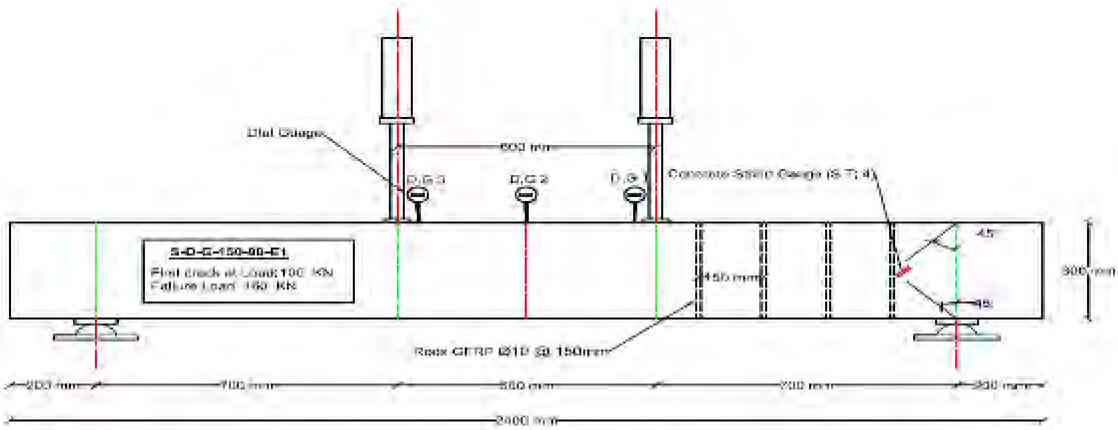

Figure 6 Test setup and Instrumrentations

TEST RESULTS

Specimens' behavior and failure modes

All specimens failed in shear and all of the strengthened beams failed due to debonding. Since the specimens had different concrete strengths, and the beams was lightly reinforced in shear at the weak side, the main factor contributing to the shear strength of the beam will be the concrete strength. The Load Level is calculated from Equation 1 to for the perpose of comparing the specimens' failure load according to the specimens' concrete strength "f_{cu}" values explained in the experimental program. The Equations are a percentage ratios of the actual load on a beam to the f_{cu} value of the same beam divided by the ratio of the Failure load on Control Beam to the Control Beam value.

$$Failure\ load\ level = \left(\frac{P_{if}/f_{cui}}{P_{cf}/f_{cuc}}\right) * 100$$

Where:

P_{if} : Failure load on selected beam

f_{cui} : Characteristic compressive strength of concrete after 28 day of selected beam

P_{cf} : Failure load of control beam

f_{cuc} : Characteristic compressive strength of concrete after 28 day of control beam

Table 2 presents a summary of the test results "the loads for one jack only".

The following sections provide a description of the specimens' behavior during testing.

Table 2 Failure Load Level

Specimen	Cracking Load* (kN)	Failure Load* (kN)	Load Level (%)	Deflection at max. load (mm)
Control	70	100	100	10
R-I.E.R.-100%	--	80	80	6.4
R-I.E.R.-70%	70	80	120	6.4
R-E.B.R.-70%	84	130	130	10.4
S-I.E.R.	70	138	138	12
S-E.B.R.	78	130	130	14

* the loads for one jack only

Control specimen

For the control specimen the first visible crack appeared at a load of about 70 kN. The crack extended from the point of loading to the support in the weak side. As loading progressed, the crack widened, and another major crack appeared in addition to several minor ones as seen in Figure 7. The specimen failed at a load of 100 kN (for one jack only). Although the failure was brittle it was less sudden than in the case of all other specimens.

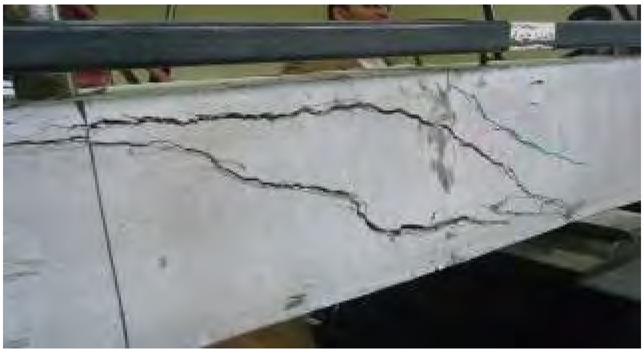

Figure 7 Crack patterns of control specimen

Strengthened Specimen using externally bonded reinforcement (S-E.B.R)

The first visible crack appeared at a load of 78 kN between the sheets. As loading progressed, cracks widened then the specimen finally failed in a brittle manner at a load of 130 kN after debonding started at the second sheet after the support. Then with further loading the failure occurred progressively one sheet at a time.

Post failure examination of the specimen showed a similar crack pattern to the control specimen as seen in Figure 8. It was noticed that the bonding failure took place in the concrete thin layer adjacent to the sheet, not in the adhesive epoxy.

Figure 8 Crack patterns of specimen S-EBR

Strengthened Specimen using internally embedded reinforcement (S-I.E.R)

For the internally embedded reinforcement specimen, the first visible crack appeared at a load of 70 kN at the loading point at a steeper angle than the case of the control specimen and even when compared with the specimen strengthened with externally bonded sheets. This can be related to the crack arresting action of the embedded bars which altered the cracking pattern compared to the control specimen. Several other cracks appeared and widened as the loading progressed, although at steeper angle as seen in Figure 9. Failure occurred suddenly at a load of 138 kN due to the de-bonding at the thin layer of concrete adhered to the CFRP bars. Some de-bonding occurred between the inner core of the CFRP bars and the outer coating of the bar as shown in figure 10. This can represent a weak point for the FRP bars as this outer coating is added to the bar to enhance its bonding properties with the surrounding concrete specimen.

Figure 9 Crack patterns of specimen S-IER

Figure 10 Debonded CFRP bar

Repaired Specimen after 70% preloading using externally bonded reinforcement (R- E.B.-70%)

The current specimen was loaded till the appearance of the first visible crack then unloaded and repaired using the externally bonded sheets. This specimen was then reloaded until failure. The first visible crack was noticed at a load level around 84 % of the maximum load of the control specimen which is significantly higher than first cracking load (70 %). This can be due to the repairing action with the cementitious material that hardened the concrete. Then the failure took place at load level of 130 % of the maximum load of the control specimen when the sheets started to fail in de-bonding mode with the concrete. This made the failure takes place in a more sudden and brittle fashion than the control RC beam specimen. This show that the EB repairing technique is a promising technique to be used in repairing RC beams cracked or damaged in shear.

Repaired Specimen after 70% preloading using internally embedded reinforcement (R-I.E.R.-70%)

For the RC beam specimen (R-IER-70%) which was loaded to the first visible crack (around 70 % of the failure load of the control specimen) then unloaded and repaired using the IER technique, when reloaded, the first visible crack appeared at load level about 70 % of the maximum load of the control beam. After the first crack took place several cracks had spread from the subjected load on the repaired side to the support. As loading progressed the cracks widened until failure occurred at load level 120 % of the maximum load of the control beam. This result shows that the IER technique is an efficient and effective technique that can be used for repairing RC beam specimens cracked in shear.

Repaired Specimen after failure (R-I.E.R.-100%)

After the failure of the control specimen, the loading was continued beyond the failure (maximum) load decreasing till about 70 % of the maximum load which caused a lot of damage to the beam itself and more than one major visible crack could be noticed very easily by visual inspection. After unloading, and since the beam suffered from intensive damage, repair works to this beam was conducted included using cementitious material as shown in Figure 5 Repaired Specimen. Afterwards the failed control beam was repaired using the I.E.R method. The control beam was reinforced with four CFRP rods150 mm apart located starting at 35 cm from the edge of the weak side in the beam. After retrofitting, beams were reloaded to failure. The specimen showed a more brittle failure than the control specimen but it only reached an 80 % level of the control beam maximum load. This may be due to the extensive damage took place during the first loading.

Deflection Behaviour

Figure 11 shows the mid-span deflection behavior of all specimens. From this figure it can be concluded that the load-deflection behavior of all repaired beams don't have a post peak behavior and it all fail in a brittle manner while all the strengthened beams and the control beam failed in a more ductile fashion and showed a post peak or post failure behavior, this may be due to the fact that the strengthened beams act as single composite unit from the beginning of the loading till failure. Consequently, the load is distributed between the concrete, stirrups, and the strengthening FRP bars or sheets leading to a behavior of more ductile fashion. On the other hand, when repairing a cracked beam, most of the load is transferred directly to the strengthening FRP sheet, or bars leading to sudden failure due to de-bonding between FRP and concrete.

Also it can be shown that a slight increase in stiffness of all repaired beams is noticed when compared with the control beam or the strengthened beams. This can be due to the major role played by the strengthened FRP bars or sheets in carrying the load in the pre-cracking stage which had a bigger role in the slight increase of the stiffness.

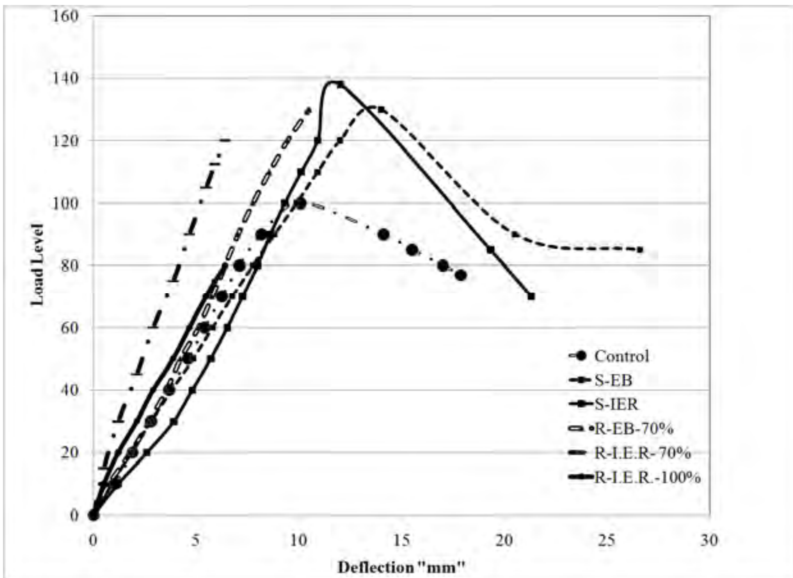

Figure 11 Deflection behavior of the different beams

Strain in steel stirrups

Figure 12 shows the load vs. strain in the second stirrup after the support for thee control beam, compared with the strain behavior of the second stirrups for all strengthened beams and the repaired beams. It is clearly shown that all the repaired beams exerted lower strain than the strengthened beams or the control beam. Based on this fact, it can be concluded that the stirrups in the repaired beam carried lower load than the stirrups in both control or strengthened beams. This may be due to the same conclusion drawn from the deflection behavior that the FRP carried most of the load in the repaired beams leading to a much lower load in the stirrups. Also it can be related to that the repaired beams are retrofitted after cracking and while unloaded to zero level. Therefore when reloading takes place, most of the load is picked up by the new repaired materials (FRP rods or sheets) leaving the stirrups with lower levels of loads. This can explain the more brittle nature of the failure pattern for the repaired beams as when failure takes place due to the de-bonding of the FRP from the concrete, there is no other part to pick up the load.

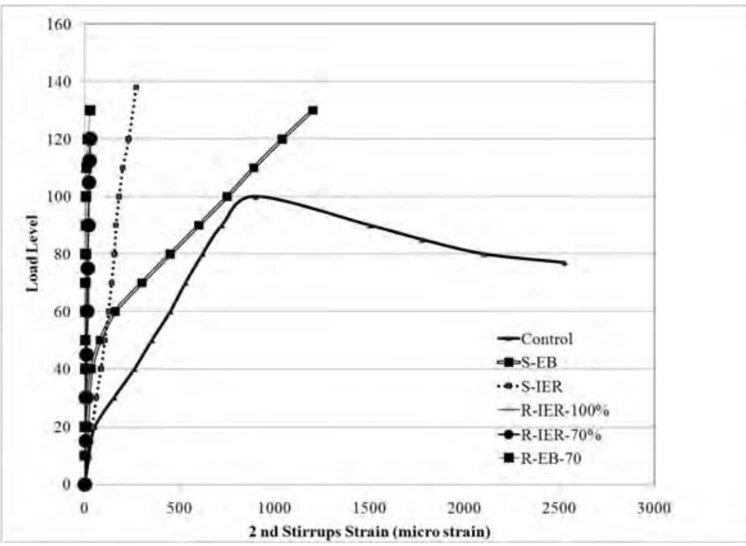

Figure 12 Second stirrups strain behavior

Figure 13 shows the load vs. strain in the fourth stirrup after the support. By comparing the strain behavior of the second stirrup with the forth stirrup, it can be found that the strain in the fourth stirrups in all beams is much higher than the second stirrups in repaired beam, this may be related to the position of the strain gauge that meet the crack propagation.

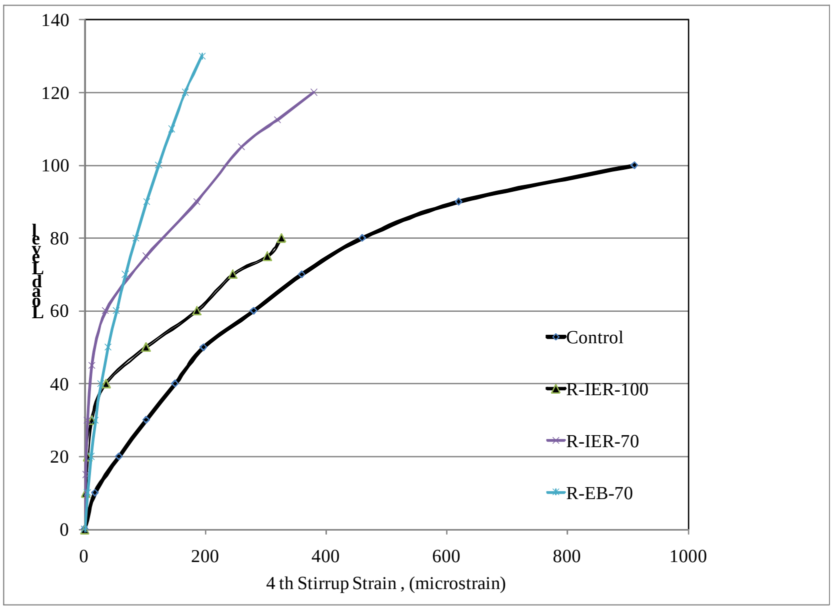

Figure 13 fourth stirrups strain behavior

DISCUSSION OF RESULTS

Effect of pre-loading Level for the repaired beams

Comparing the repaired beams (R-I.E.R.-70%) and (R-I.E.R. - 100) pre-damaged under two different pre-loading levels 70 % and 100 % of the failure load respectively, it was found that the repairing technique using I.E.R. is an effective technique for repairing beam specially if the beams are repaired after the appearance of the first visible crack which corresponds in this research to 70% from the failure load. Also it is noticed that when repairing beams just after first crack formation (loading up to 70% of the ultimate load) exceeds the control beam (without strengthening) by 20% strength gaining.

On the other hand, when repairing the control specimen after fully damaged and after a continuing damage till the dropped load reached around 70% of its ultimate load, it was seen that the beam could not pick a load more than 80 % of its original ultimate load before loading (at the first loading). This shows the importance of the quick actions for making the repair decision for the cracked beams not to wait until great damages are taking place.

Comparing strengthening versus repairing methods

Generally, by comparing the results of all specimens, it can be seen that repaired and strengthened specimens using both techniques (IER and EB) showed almost comparable results. Also, these beams showed almost the same mode of failure which is de-bonding in the epoxy layer attached the CFRP with concrete substrate.

Generally, it was noticed that the RC beam specimens repaired using both techniques (IER and EB) gained a slight increase in the stiffness compared with the strengthened specimens and even the control specimens. On the other hand, the strengthened RC beam specimens showed a more ductile fashion of failure than the repaired specimens based on the post peak behavior of the strengthened specimens which shwed a gradual decrease in load while the repaired RC beam specimens suffered a more sudden failure and sudden drop in the load after the peak load.

Also, comparing the IER repairing technique with the EB one, it can be seen that both techniques showed almost very near failure load and also almost the same mode of failure. This indicate that both techniques are valid and appropriate for using as a promising repair technique especially that both techniques showed 20 -30 % higher failure load than the control RC beam specimen. Also their results were nearly comparable with strengthened RC beam specimens.

CONCLUSION AND RECOMMENDATION FOR FUTURE WORK

Based on the results of this experimental program the following conclusions and recommendations for future work could be made;

- Repairing the beams for shear using both internally embedded reinforcement and externally bonded method is an effective technique for repairing pre-damaged RC beams in shear.
- When using the IER technique, it is recommended to start the repairing action at minimum damage to the RC beams to gain the best strengthening for the beams.
- The strengthened RC beam specimens failed in a more ductile fashion and showed a post peak or post failure behavior than the repaired RC beam specimens.
- Using the internally embedded strengthening technique can provide almost the same effect as externally bonded technique.
- Further research is needed to study the de-bonding behavior of IER and the effects of the different parameters like the bonding agent, angle of inclination of the IER, the spacing between the IER, etc. on its behavior.

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