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# Current Practices of Retrofitting and Strengthening of Rc Structures: A Review

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***Abstract:*** *This paper presents a literature review concerning the mechanical properties such as flexural strength, bond strength, shear strength and compressive strength of plain cement concrete and reinforced cement concrete strengthened with Fibre Reinforced Polymer (FRP). It starts with the introduction and important behavioural response of FRP. A brief insight is given on the influence of using FRP on various structural members including concrete beams, columns, corbels and beam-column joints. Different techniques to repair and strengthen the damaged structural members are also given. Externally bonded reinforcement (EBR) and externally bonded reinforcement on groove (EBROG) technique which is an interesting alternative to the conventional method is presented in this paper.*
***Keywords:*** *Fibre Reinforced Polymer, Concrete, Flexure strength, Repair and strengthening technique*

## I. Introduction

In the last decade it is witnessed that the interest of researchers has been inclined towards replacing conventional materials such as steel and concrete with fibre reinforced polymer (FRP) composites for retrofitting and strengthening of the concrete structures. Due to flexibility in application, low stiffens-weight ratio and resistance to corrosion, these FRP composites have remarkable advantages over conventional structural materials. [10] Conventional repairing techniques which include steel and cementitious materials do not always provide optimum solution. Repairing and strengthening with FRP can offer a more significant and economical alternative to the conventional repairing techniques. [19] It is shown in the study that polymer concrete is stronger than the cement based concrete. [41] Nowadays Polymer Concrete gets used very extensively but it also exhibits brittle properties which can be improved by using laminates or strengthening by other flexible materials such as FRP. Hence it is very important to develop a better PC system. [2] According to [38], strengthening the structure with FRP is very good solution for structure to resist against sudden loading. In order to enhance the flexural strength of the existing structures, the externally bonded composites such as FRP on the tension face of the RC structure has been widely used. In fact various comparable experimental and analytical studies have stated that EB FRP can be surely used to improve the structural behavior of the concrete members such as ductility, load carrying capacity, stiffness and durability. [42]

## II. Literature review

The idea followed in this literature review involved the assessment of the main properties of concrete enhanced with FRP. Afterwards, publication list was identified as per the title, content and theme of this paper. As all the publications were individually studied, all the relevance information regarding effect of FRP on flexural strength, bond strength, shear strength and compressive strength of plain cement concrete and reinforced cement concrete was gathered and presented in this paper.

### 2.1 Bond Behavior

D. Mostofinejad et. al. [22] used EBROG and EBR techniques to investigate the effect of compressive strength (i.e. 26, 32 and 43 MPa), depth of groove (i.e. 2,5,10 and 15 mm) and thickness of CFRP (i.e. 13 mm, 17 mm and 26mm)on CFRP concrete. Experiments revealed that EBROG technique was better than EBR technique and with increase in depth of groove the bond strength was increasing and slight shorter bond length was observed with increase in compressive strength. L. Gao et. al. [15] performed an experimental and numerical study on the bond behavior of joints of concrete to FRP strip strengthen by mechanical fastener. In order to obtain the interfacial bond behavior and bond slip relationship total 7 single-lap shear tests were performed. Specimens with FRP strip only, FRP strip with two fasteners and FRP strip with three fasteners were prepared. Numerical study was also done on bond slip behavior. During the failure of concrete, a layer of concrete got peeled away and got attached with FRP strip. Also, the results obtained from the numerical modeling had good consistency with the experimental results.

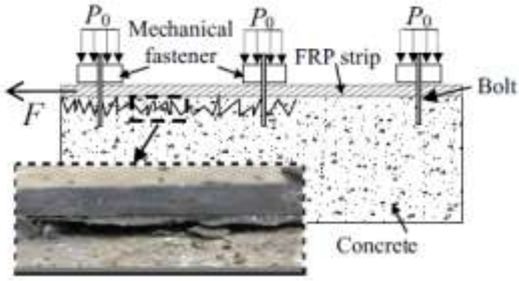


**Fig. 1 Mechanism of HB joints after debonding. [14]**

D. Mostofinejad et. al. [10] investigated the influence of volume of coarse aggregate on bond strength of CFRP concrete by using EBR technique. CFRP sheets of size 200 mm x 50 mm were used to strengthen the 52 specimens of concrete. Variation in the volume of coarse aggregates and fine aggregates was used, where specimen were casted from 0% coarse aggregate-100% fine aggregate to 100% coarse aggregate- 0% fine aggregate. Direct single-lap shear test and Particle Image Velocimetry (PIV) were conducted on specimens. The single lap-shear test results revealed that variations in fine fraction led to changes in bond strength such that fine fraction values of 0.3–0.6 led to reduced bond strength while those from 0.6 to 1.0 increased it. C. Yuan et. al. [8] conducted an experimental study in which effects of different sizes of aggregate was evaluated on the Bond behavior of CFRP sheets and concrete by performing single-lap shear test. Several parameters such as effective bond length, maximum bond stress, debonding load, slip at maximum shear stress and bond slip relation was taken into consideration in this study. Aggregate sizes used were 5-10 mm, 10-15 mm and 15-20 mm. Result showed that with increase in size of aggregates interfacial shear stress between CFRP sheets and concrete was decreasing due to reduced tensile strength of concrete, whereas bond length was increasing with increase in size of aggregate. Significant increase in slip at maximum shear stress was also observed with increase in size of aggregate. Y. T. Obaidat et. al. [18] investigated the effect of plate-configurations of CFRP on partially damaged reinforced concrete beam-column joint. Damage was introduced up to 80% of the ultimate load to the concrete-beam joint specimen by subjecting it under cyclic loading and then afterwards strengthening by using plane configurations of GFRP was done. Total number of eight RC specimens was casted and tested in order to find out the repairing efficiency for improving strength. Result revealed that the load carrying capacity was increased significantly by using CFRP-planes whereas failure pattern was changed into debonding of CFRP from diagonal cracks. By using different CFRP plane techniques the load carrying capacity was increased up to 64% to 148% with respect to control RC beam column joint. Results showed that failure of control joint due to lack of shear reinforcement. A. Tajmir-Riahi et. al. [6] used externally bonded reinforcement on groove (EBROG) technique in their study to improve the bond strength of CRPF concrete. Their focus was to improve bond resistance of a single groove without disturbing the adjacent grooves. Several parameters such as ultimate load bearing capacity, efficient bond length and external bonded reinforcement (EBR)'s effect was considered. CRPF specimens were tested under single lap shear test. Results revealed that 40% of increment in bond resistance was noticed in EBROG technique when shifted from EBR technique. Different groove sizes were tested in EBROG technique, results showed that with increase in dimension of groove the bond strength was decreasing.

The level of effectiveness of a FRP strengthening Technique is dependent on the Fibre Reinforced Polymer interface's bond behavior. Various types of debonding failure such as intermediate crack formation debonding and concrete cover separation can be observed in concrete when subjected to extensive shear loading. C. Chen et. al. [5] conducted a study on transverse grooves effect on bond behavior of fibre reinforced polymer concrete. Effect of groove's characteristics such as width, depth and clearance on bond behavior of FRP concrete was investigated by casting 27 concrete blocks. The bond strength of concrete epoxy interface was improved by providing transverse groove. Image analysis was done which showed that fracture interface was shifted to concrete–epoxy interface to FRP-epoxy interface, epoxy interface, and dual-interface. Increased interfacial slip was observed due to the application of introduced transverse grooves.

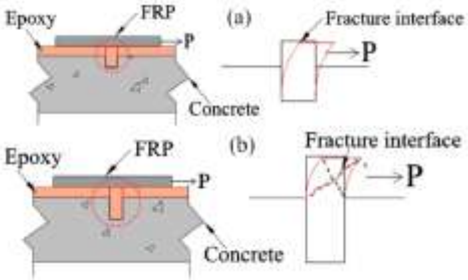


**Fig. 2 Effect of groove depth on fracture interface: (a) small depth; and (b) large depth. [5]**

N. Moshiri et. al. [11] Conducted both experimental and analytical study on bond behavior of CFRP concrete by using EBROG and EBR technique. Pre cured CFRP strips were used for strengthening and 10 tests of direct single–lap shear were conducted. Also, analytical study was done in order to obtain bond shear-stress behavior for EBROG technique. Bond resistance was found more in EBROG technique rather than EBR technique. In EBROG method grove size of 5 mm x 5 mm attained more than 90% increase in bond capacity. C. Chen. et. al. [17] performed extensive study on the influence of method of surface preparation on Fibre reinforced Polymer Concrete bond performance. Two factors were considered to quantify the level of surface preparation such as aggregate's area ratio and roughening depth. To investigate the influence of these two factors 36 concrete blocks were tested under direct pull out force until failure. Test results showed that by increasing the roughness depth in the aggregates the interfacial failure plane got shifted from FRP concrete interface to the concrete interface. The quantitative image analysis (QIA) showed that the local fracture interface was shifted to concrete interface and surface preparation changed the pullout force increased with the percentage of interfacial failure.

### 1.2 Shear Strength

Y. S. S. Al-Kamaki et. al. [30] presents a study in which behavior of reinforced concrete short corbels were strengthened by providing external CFRP fabrics. In this study few parameters for testing were considered which were external composite sheet configurations and amount of internal secondary reinforcements. Result showed that by strengthening the load bearing capacity was increased by 27% also the width and length of shear cracks formed at 45 degree was restricted.

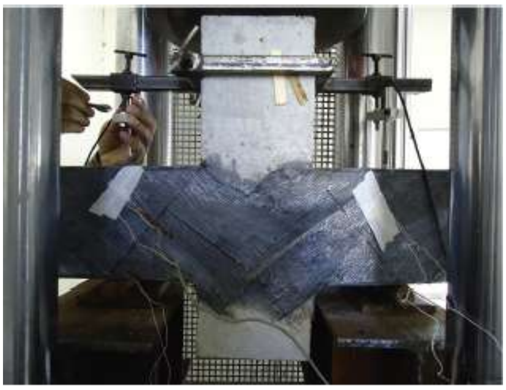

**Fig.3 Specimen setup**

H. Zhang. et. al. [9] studied the influence of corroded reinforcement on Reinforced Recycled Aggregate Concrete beam's shear behavior strengthened by CFRP. Total number of 8 specimens of beam was subjected to accelerated corrosion consequently from 1 to 7 days to obtain the loss in mass in stirrups of 1%, 3%, 5%, 7%, 9%, 11% and 13% respectively. A very little difference in shear was observed because of the variation in corrosion. Diagonal shear cracks were restricted very effectively by using CFRP sheets, Also there was delay in critical cracks. CFRP sheets did not reach its ultimate strength when it got debonded. The CFRP strengthening effect of corroded reinforced recycled beams was more obvious than the corroded reinforced concrete beams under the same corrosion level. E. Oller et. al. [7] strengthened the T-beams in shear by providing external bonded U- shaped CFRP sheets with and without anchorages. Also, the contribution of concrete, steel reinforcement and carbon fibre reinforced sheets in the behavior of shear strength was checked and Strength was found more when used with anchorage. Study concluded that flange of the T beam contributed 45% of total shear strength and FRP sheets proved effective only when anchorage was provided. M. Kim et. al. [38] investigated the influence of CFRP on normal concrete subjected to impact loading. In this study the width and spacing of the CFRP wrap was varied and tests were performed with the drop weight test machine, where weight of the drop hammer was 461 kg and it was dropped from the height of 300 mm. Beams with the 20 mm and 40 mm CFRP did not completely failed though the deflection was similar to normal concrete beam. Also the shear strength of the beams enhanced significantly with CFRP.

### 1.3 Fracture and Flexure Behavior

The two parameter model study carried out by Reis and Ferreira [2] in which by using the flexural behavior of Polymer Concrete incorporated with chopped carbon and glass fibres reinforced polymer was investigated. Epoxy resin was used as polymer. In this direct method the crack tip opening displacement (CTOD) and critical stress intensity factor was calculated. Results obtained from two parameter test clearly stated that glass fibre improved the fracture toughness by 13%. Carbon Fibre Reinforcement improved the property significantly by 29%. Also, it was observed that polymer concrete has fracture performance than plain cement concrete. R. Z.. Al-Rousan et. al. [25] used CFRP sheets, CHRP anchorage and Discontinues structural synthetic fibre to increase the flexural strength of concrete. Total 72 prism specimens of 150 mm x 150 mm were casted and tested under for point bending test. Significant decrease was recorded in crack width with increase in CFRP sheets, but crack length was increasing, whereas, both width and length both decreased with increase in DSSF dosage. Z. Zhu et. al. [15] investigated the flexure fatigue behavior of RC beams strengthened with side near surface mounted non-prestressed and prestressed CFRP. Total six beams were casted, three static beams and three fatigue beams. In order to introduce the initial damage fatigue beams strengthened after subjected to 2 million fatigue cycle first and then subjected to 50,000 fatigue cycles again. Ultimate load carrying capacity was found more in strengthened beam as compare to no strengthened beam. Where, In case of flexure the prestressed beams performed better than non-prestressed beam. In conclusion the side near surface mounted technique is effective and feasible technique in order to improve the flexural and ductility properties.

M. Chellapandian et. al. [12] conducted experimental and finite element studies to check the influence of hybrid FRP technique on reinforced concrete elements. Different strengthening techniques such as (i) near surface mounting (NSM), (ii) external bonding (EB) and (iii) hybrid strengthening using a combination of NSM carbon FRP laminates and EB CFRP fabric were compared. To stimulate the behavior of RC beams with and without FRP strengthening a 3-D model was developed. Increase of 60% was observed when hybrid FRP technique was used. Also, maximum displacement of hybrid FRP strengthened beams was lesser than NSM technique. Peak strength in NSM was improved by 85%.. M.R.E.F. Ariyachandra et. al. [32] investigated the effects of external surface roughness and bond improving methods on the flexural behavior on reinforcement concrete beams along with CFRP strips. External surface was prepared by different methods such as with san paper, sand blasted and chipped. In some specimens polyester mesh was also provided and compared with other specimens. Result indicated that CFRP epoxy polyester mesh showed better performance than CFRP strengthened beams. A. Jawdhari et. al. [35] used CFRP rod panels (CRP 195) for strengthening the beams in flexure response. Five specimens with different strengthening combinations were tested. Beam capacity was increases by 104% when strengthen with CRP 195. To validate the load-defection curve and ultimate load an analytical model was prepared. The response of curves produces from analytical model has quite similar to the curves produced from experimental work. The influence of thickness of FRP laminates on flexural properties of hybrid concrete was investigated by C. Chen et. al. [13]. Four point bending test was performed on 10 beams of size 150 mm x 250 mm x 2400 mm with and without hybrid strengthening i.e. fastener. Confining influence and thickness of the laminates was varied in each specimen. Result revealed that both performance in ductility and load carrying capacity was improved when fasteners were used. Increase in flexural properties was observed with increase in the thickness of laminates. In order to obtain the optimum load carrying capacity and ductility performance a design model was proposed, through which accurate failure limits got predicted. N. M. Banjara et. al. [27] investigated the influence of deficient reinforced concrete beam's flexural behavior strengthen by CFRP under static and fatigue loading. Two types of beams along with control beam, one with 20 % deficient reinforced and other 30% deficient reinforced beams were tested and in result it was found that load carrying capacity is lowered by 8% and 30 % respectively. Then beams with layer of CFRP were tested and result was found beyond the strength of control beam's strength. Comparison was made with numerical approach to validate the experimental work. Result along with crack formation was coming similar in that approach.

M. I. Kabrit et. al. [36] casted three different RC beams with three different admixtures i.e. Fly Ash, Waste Rubber and Polypropylene. The control beams were damaged up to ultimate load and then strengthen with CFRP sheets at soffit and anchored with complete CFRP wrap. Repaired beams were then subjected to four point bending test in order to analyze the stiffness, strength and ductility stiffness and strength of first two mixes was improved significantly when compared with control beam but was half when mixed with polypropylene. In addition to that analytical model was prepared to evaluate the optimum results when beams strengthen with CFRP sheets and CFRP anchorage. M. Chellapandian et. al. [4] investigated the flexural and axial compression behavior of RCC columns. The axial compressive and bending loads were applied at different eccentricities to damage the columns and then different Fibre Reinforced Polymer Techniques were used to strengthen and repair the RCC columns. Carbon Fibre Reinforced Polymer laminates was used for Near Surface Mounting (NSM) and hybrid strengthening by combination of Near Surface Mounting (NSM) and External Bonded (EB) fabrics. Ratio from 0.4% to 1.6% was varied for NSM CFRP laminates and significant improvement was observed in bearing the peak load and bending by increasing the area of NSM laminates. For Hybrid combination of NSM CFRP and EB fabric 0.70% ratio was used. Strength was restored once again when strengthened by combination of NSM CFRP and EB. [33], investigated the flexure property of pre-loaded reinforced concrete beams which were latterly strengthened with pre stressed CFRP sheets and normal CFRP sheets. Comparison was made between control beams and beams with normal sheets and between beams with pre stressed CFRP sheets and beams with normal CFRP sheets. Parameters examined were (i) pre-tensioned strain level, (ii) CFRP reinforcement ratio, and (iii) sustained loading level. Results showed that first two parameters has significant influence on the stiffness and flexural behavior beam, whereas, third parameter is less effective. Experimental results were validated with numerical approach and good correlation was found when compared.

Asad ur Rehman Khana and Shamsoon Fareed [37] EBR technique to strengthen the RC beam in flexural response. In this study total six beams were casted strengthened with CFRP wraps with and without CFRP anchorage along with control beam. Stiffness, ductility and load carrying capacity was enhanced by strengthening the beams. Hamad A. A. A. et. al. [34] performed an experimental study on preloaded concrete beam to evaluate the flexure property. Total 5 beams with same reinforcement and same dimensions were casted which were strengthened by RC and CFRP. Comparison was made between beam strengthen by RC and beam strengthen by CFRP. Results showed that preloading level has effect on deflection and load carrying capacity of the RC beams strengthen with RC whereas it has no effect on same properties of the RC beams strengthen with CFRP layers at the soffit. Decrease in deflection and load carrying was observed when pre loading was decreased. CFRP layer decreased the mid span deflection and behavior of the cracks, whereas ductility and strength was improved. Y. Zhou et. al. [17] casted five rectangular reinforced concrete beams with shear-strengthening of U-shaped CFRP strips, one beam as control beam, one beam with external bonded U-shaped CFRP strips and other with hybrid bonded U-shaped CFRP strips. Tests were performed under consideration of several parameters such as load-deflection behavior, Cracks angle, flexure failure behavior, distribution of strain and development of CFRP strips and stirrups. Hybrid CFRP beams significantly increased the shear strength as compare the other types of beams, also the shear cracks got form at the angle of 38° to 43°. Same pattern was followed by the beam when ductility behavior was investigated. Maximum strain and effective strain was larger in the hybrid beams and also debonding was much slower than other specimens.

A.S.D. Salama et. al. [26] unlike conventional technique used a new technique to strengthen the concrete in flexure. Instead of beam soffit the CFRP sheets were provided at side as well as at bottom. Total 9 beams were casted along with one control beam. Result showed that strength was increased 62% - 92 % with bottom bonded CFRP and 39.7% - 93.4% with side bonded CFRP with respect to control specimen. Later results were also validated with analytical expression derived from ACI 440.2R-08 guidelines and difference between experimental work and analytical result was varying from 2.4% to 6.8%.

A. Ali et. al. [29] presented a work in which flexure strength of the self consolidating concrete was improved by using CFRP sheets and further on by providing mechanical anchors to the beam specimens. In the observations it was stated that as soon as debonding started the CFRP sheets started getting separated but debonding was delayed when CFRP sheet was provided at bottom soffit with anchors. [28], Analyzed the brittle behavior of the different column and beam joints by using FE software ABAQUES and provided a optimum solution i.e. FRP wraps to increase the ductility strength of the joints and stirrups continuity affects and increase the shear strength.

**2.4 Compressive Strength**

Strengthening of concrete structures is being done by Uni-directional CFRP composites, but their strength in axial compression is found very less. [24], investigated the effect of transverse confinement to improve longitudinal compressive behavior of composites. Results showed that cross-section and shape has no effect on longitudinal compressive strength. S. Suon et. al. [3] performed an experimental study on compressive behavior of concrete by adding new composite polymer extracted from Basalt Rock, Basalt Fibre Reinforced Polymer (BFRP). A total of 56 circular and non circular concrete specimens jacketed with BFRP composite without using steel reinforcement were tested under axial compression to failure. LVDT’s and strain gauges were used horizontally and vertically to obtain result. In result it was observed that with increase in layers of BFRP the ultimate stress and strain of all confined specimens was enhancing. Different responses were observed such as strength softening, after plastic behavior and strength hardening after reaching the ultimate peak strength for different sample shapes respectively.

P. Asokan et. al. [1] evaluated the effects of including 5%, 15%,, 30% and 50% Glass Fibre Reinforced Polymer waste powder in concrete composite and observed that with increase in the percentage of GFRP powder waste in concrete the compressive strength was decreasing. However, the strength was increasing with increase in curing period i.e. the optimum compressive strength observed was 45.75 N/mm$^2$ on 180 days of curing. By incorporating 30% and 50% of GFRP waste powder the compressive strength of 29.5N/mm$^2$ and 19 N/mm$^2$ was attained respectively. Wei Zhou and Xinying Xie [16] emphasizes on the flexural behavior of continuous unbonded post-tensioned (UPT) beams strengthened with CFRP laminates subjected to flexural loading till failure. The aim of this study was to predict the flexural behavior of continuous unbonded post-tensioned (UPT) beams lead by series of tests for two-span strengthened UPT beams and considering the global reinforcement indices in both the sagging and hogging regions and the span-depth ratio .During the failure of specimens it was observed that the cracks formed in both hogging and sagging region, where as crushing of concrete took place in sagging region. Cracks got more widened and extended with increase in load to failure. The pattern followed in failure was crushing of concrete from the mid span followed by debonding of the CFRP laminates. R. Ismail et. al. [20] performed compressive strength test on concrete cylinder (300 mm x 150 mm) fully confined with CFRP sheets and partially confined with horizontal and spiral CFRP strips at the spacing of 20 cm, 40 cm and 60 cm. Specimen with horizontal CFRP strip at spacing of 20 cm attain the yield strength of 86.56 MPa i.e. enhanced the strength by 71%. Hence was adequate. G. Yongchang. Et. al. [21] evaluated the CFRP single to multilayer effect on Normal Strength concrete and High Strength Concrete damaged at different percentages such as 70%, 755, 78% and 80%. Total 60 concrete cylinders, 30 NSM and 30 HSC were casted and subjected to compression test. Result showed that increase in layers of CFRP was effective the ultimate strength. Also, effect was more significant for NSC specimens compare to HSC specimens.

J. Yang et. al. [40] casted 16 high strength concrete columns out of which 14 columns were confined with CFRP and subjected to eccentric compression loading with the eccentricity of 50 mm and 100 mm. Two parameters such as number of CFRP layers and pre damaged state were varied and failure modes were analyzed. In results it was observed that ductility and load carrying capacity of the column increased significantly. Mechanical performance was optimum when at eccentricity of 50 mm columns were confined with CFRP wraps, but at the eccentricity of 100 mm the energy absorption and ductility was improved. Because the columns were pre-damaged which affects the strengthen rate very much. Then stress strain model was developed from the large data obtained from tests and compared with the experimental results. In comparison with the experimental and analytical results, good agreement was found between both. J. Wang et. al. [23] studied the compressive response of hybrid steel concrete composite column strengthened with CFRP considering parameters such as cross-sectional shape, the width of grooves on the steel tube, and the number of CFRP sheet layers by testing 14 specimens. They founded that with increase in CFRP layers the load carrying capacity and axial deformation was increasing in circular column but same was not followed in case of square column. K. S. Alotaibi and K. Galal [31] performed an experimental study on reinforced concrete masonry columns confined with CFRP loaded under concentric and eccentric loads i.e. axial compressive load and tensile load. 28 columns were tested and tests revealed that CFRP jackets increased the axial compression load and axial deformation with respect to unconfined columns. Also, the post peak behavior was also enhanced with CFRP jacketing. L. Na. et. al. [39] performed axial compression test eight specimens of concrete filled steel tube columns with height ranging from 588 to 2688 mm strengthened with CFRP layers. Result revealed that CFRP layer provided sufficient confinement to the columns thus significantly improving the behavior of column. Result was also validated by comparing with analytical methods.

## III. Conclusion

The use of FRP for repairing and strengthening the plain cement concrete and reinforced cement concrete has been analyzed in this study. The following conclusions can be drawn from this study.

A number of techniques to utilize the maximum efficiency of FRP were examined in this paper such as number of layers of FRP, FRP strips with and without FRP anchorage, fully and partially confinement of the FRP, FRP strips anchored with mechanical fasteners, FRP strips at horizontal and inclined pattern, Near Surface Mounting (NSM), Externally Bonded Reinforcement (EBR) and Externally Bonded Reinforcement On Groove (EBROG).

Strengthening techniques increased the load carrying capacity of the specimen and shear cracks produced at 45 degree were restricted. Also, the width and length of the cracks was reduced.

The mechanisms used increased the ultimate load in FRP concrete beams and interfacial failure plane got shifted from FRP concrete interface to the concrete interface. Different groove sizes were tested in EBROG technique, results showed that with increase in dimension of groove the bond strength was decreasing.

These techniques proved very effective on the flexural behavior of concrete. Flexural response was significantly enhanced and deflection noted was also reduced.

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