State-of-The-Art Review of FRP Strengthened RC Slabs

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Abstract— Many concrete structures are getting weakened or collapsed due to corrosion of steel reinforcement in structures and other factors. Rehabilitation and strengthening of concrete structures with FRP (Fibre Reinforced Polymers) has been a useful technique since last few years. FRP sheets or plates are very suitable for strengthening not only because of their strength, but also due to the simplicity in the application. In this review paper, different strengthening techniques using FRP and other materials are reviewed. It can be concluded from the literature review that FRP is one of the efficient option for strengthening in either of the case like increasing the load carrying capacity of structures or to restore the original capacity of the structure after distress due to any means.

Key words: Concrete structures, FRP, strengthening, strengthening techniques

I. Introduction

Fibre Reinforced Polymer (FRP) is a composite material made of a polymer matrix reinforced with fibres. The fibres are mostly glass, carbon, aramid, or basalt; whereas, other fibres such as paper, wood or asbestos are also used for specific applications. FRPs are commonly used in the aerospace, automotive, marine, and construction industries. The applicability of FRPs for strengthening of concrete structures as an efficient option has been actively studied in numerous research laboratories and professional organizations around the world.

A. Use of FRP's:

Strengthening of concrete structures must be considered when the existing structure deteriorates or any alteration to the structure has to be made due to which the structure may fail to serve its purpose. In some cases it can also be difficult to reach the areas that need to be strengthened. When strengthening is going to be undertaken all failure modes must be evaluated. The strengthening should be designed with consideration to minimize the maintenance and repair needs.

Use of FRP in strengthening process is increasing day-by-day due to its numerous advantages, i.e. corrosion resistance, lightweight, ease of installation, less maintenance, ideal for external application.

B. History of FRP's:

Bakelite was the first fibre-reinforced polymer. Dr. Baekeland had originally set out to find a replacement for shellac (made from the excretion of lac beetles). Chemists had begun to recognize that many natural resins and fibers were polymers, and Baekeland investigated the reactions of phenol and formaldehyde. He first produced soluble phenol-formaldehyde shellac called "Novolak" that never became a market success, and then turned to developing a binder for asbestos which, at that time, was moulded with rubber. By controlling the pressure and temperature applied to phenol and formaldehyde, he found in 1905 he could produce his dreamed-of hard mouldable material (the world's first synthetic plastic): Bakelite. He announced his invention at a meeting of the American Chemical Society on February 5, 1909.

The development of fibre-reinforced plastic for commercial use was being extensively researched in the 1930s. In the UK, considerable research was undertaken by pioneers such as Norman de Bruyne. It was particularly of interest to the aviation industry.

C. Advantages of FRP's:

FRP materials have very good durability. They are available in long lengths and hence eliminate the problems of joints and splices. The curing period for FRP's is very less, i.e. they cure within 24 hours. Light-weight construction is possible with such materials. The resistance against corrosion is also one of the fruitful advantages of such materials. The installation process is also simple and it requires minimum maintenance even after construction. FRP's are ideally suited for any external application.

D. Structural Applications of FRP's:

FRP can be applied to strengthen beams, columns and slabs of buildings and bridges. It is possible to increase the strength of structural members even after they have been severely damaged due to loading conditions. In the case of damaged reinforced concrete members, this would first require the repair of the member by removing loose debris and filling in cavities and cracks with mortar or epoxy resin. Once the member is repaired, strengthening can be achieved through wet, hand lay-up of impregnating the fibre sheets with epoxy resin then applying them to the cleaned and prepared surfaces of the member.

II. Various Strengthening Techniques

The most common used flexural strengthening techniques with FRP composites are:

1) Externally bonded reinforcement (EBR) using FRP sheets and strips, &
2) Near surface mounting (NSM) method using FRP strips.

A. Externally Bonded Reinforcement (EBR):

The Externally Bonded Reinforcement (EBR) is most commonly used due to its simple installation. Different systems of externally bonded FRP reinforcement (FRP EBR) exist, related to the constituent materials, the form and the technique of the FRP strengthening. In general, these can be subdivided into "wet lay-up" (or "cured in-situ") systems and "prefab" (or "pre-cured") systems.

1) Wet Lay-Up Systems:

Dry unidirectional fibre sheet and semi-unidirectional fabric (woven or knitted), where fibres run predominantly in one direction partially or fully covering the structural element. Installation on the concrete surface requires saturating resin usually after a primer has been applied. Two different processes can be used to apply the fabric:

The fabric can be applied directly into the resin which has been applied uniformly onto the concrete surface, The fabric can be impregnated with the resin in a saturator machine and then applied wet to the sealed substrate.

Fig. 1 : Wet lay-up of CFRP sheets

2) *Prefabricated Elements:*

Pre-manufactured cured straight strips, which are installed through the use of adhesives, are used. They are typically in the form of thin ribbon strips that may be delivered in a rolled coil. Normally strips are pultruded. In case they are laminated, also the term laminate instead of strip may be used.

Fig 2: Application of prefabricated strips

B. *Near Surface Mounted (NSM) Reinforcement:*

The Near-surface mounted reinforcement technique is developed for strengthening concrete structures. The technique was developed as an alternative to externally bonded fibre composite materials.

The process involves cutting a series of shallow grooves in the concrete surface in the required direction. The depth of the groove must be less than the cover so that the existing reinforcement is not damaged. The grooves are then partially filled with epoxy mortar into which pultruded carbon fibre composite rods or strips are pressed. The remainder of the groove is then filled with epoxy mortar and the surface is being levelled. The approach can be used to increase the flexural (bending) of beams and slabs, or the shear capacity of beams. It can also be used for strengthening concrete masonry walls.

III. Yield Line Theory

The yield line theory is an ultimate load theory for design of R.C slabs. The yield line theory is a powerful tool in analysis as it enables determination of failure moment in slabs of rectangular as well as irregular shapes for different support conditions and loadings. In this theory, the strength of slab is assumed to be governed by flexure alone; other effects such as shear and deflection are only required to be checked, if necessary.

The yield line is defined as a line in the plane of the slab across which reinforcing bars have yielded and about which excessive deformation under constant ultimate moment, continues to occur leading to failure.

A. *Behaviour Of One Way Slab Up To Failure*

When a uniformly loaded one-way simply supported under-reinforced slab is designed, a plastic hinge is developed at the point of maximum bending moment on loading, at ultimate state (for a specific strip). When all the points (plastic hinges) of strips of slabs are connected they form a yield line. And at this time, we can say that collapse mechanism has formed.

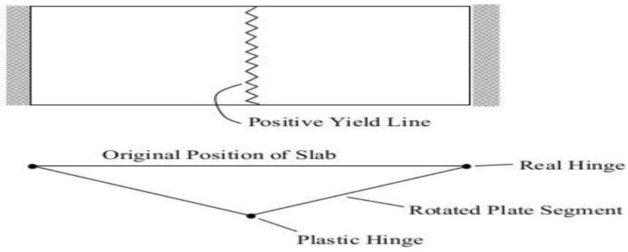

Fig. 3: Positive Yield Line for One-way simply supported slab

B. *Assumptions of Yield Line Theory:*

The failure mode is arrived at on the basis of following assumptions:

1) The failure is due to complete yielding of reinforcing steel along the yield lines.
2) The bending moments and twisting moments at ultimate state are uniformly distributed along the yield line.
3) At failure, the yield line divides the slabs into individual segments.
4) The plastic deformations are much greater than the elastic deformations which can be considered as negligible.

C. *Guidelines for Predicting Yield-line Patterns:*

The following guidelines can help to determine the yield line:

1) Yield lines are straight lines.
2) Yield lines end at the slab boundary.
3) Yield lines pass through the intersection of axes of rotations of adjacent elements.
4) Axes of rotations generally lie along lines of supports and pass over the columns.

IV. Review of Literature

A vast variety of work has been done regarding strengthening of RC slab with different materials and different techniques but a limited amount of work has been done on the strengthening of concrete slab with opening or cut-outs. Concise observations related to strengthening of slab are discussed here.

A. Review of Literature Strengthening Of Slabs with Openings:

The paper reports field tests on the use of Carbon Fiber Reinforced Polymers (CFRP) strengthening alternatives to restore the flexural capacity of the RC slab after having large openings cut out in the positive moment region. The uniqueness of this study is that the tests were performed on an existing multi-storey RC structure that was scheduled for demolition. Testing a real structure allowed incorporating factors and boundary conditions that typically cannot be simulated in the laboratory. The results of this study showed that the use of EB CFRP laminates slightly increased the flexural strength of the slab with opening, while significantly enhancing its stiffness [1].

In this paper, the prototype one-way RC slabs with openings were strengthened with externally bonded carbon fiber-reinforced polymer (CFRP) systems and subjected to concentrated line loads. The results were compared to those of a solid slab without opening and a slab with an un-strengthened opening. The CFRP system proved to be effective in enhancing the load-carrying capacity and stiffness of RC slabs with an opening, provided that premature failure due to CFRP debonding is excluded. The results showed that CFRP sheets appear to provide a more effective strengthening system than CFRP strips because of premature debonding failure due to the higher stiffness of the latter [2].

In this paper an experimental work was conducted to determine the structural performance of one-way reinforced concrete (RC) slabs with rectangular opening. The results concluded that the reduction of 15% area due to the rectangular opening located at the centre of the RC slabs reduces 36.6% of flexural strength. It also showed that the cracking pattern found in the opening slabs show a high concentration stress occurred at the corner of the opening when vertical load is applied [3].

In this study analytical work was conducted rather than experimental work and still the results turned out to be positive. The nonlinear finite element method was used to analyze full-scale reinforced concrete slab with opening strengthening with overlay concrete or CFRP sheets. The results showed positive response when slab was strengthened with CFRP sheets, as CFRP sheet strengthening increased the load carrying capacity of the slab with cutout with different value depending on the arrangement of CFRP sheet and varying from 10 to 65 % [4].

The main purpose of this research is to study analytically the strengthening of a reinforced concrete bridge slabs due to excessive loads, using externally bonded FRP sheets technique. The results showed that by increasing CFRP sheet width it increases the slab capacity and toughness and also that by decreasing CFRP sheet spacing increases the slab capacity and toughness [5].

This study is based on the fact that stress and displacement variation depends on boundary conditions of slab. The aim of the study to know the variation of displacement, stresses, in slab with different boundary conditions. The study showed that displacement is highest in slab having simple support on all sides and stresses are least in same slab along the edges. Also slab with fixed support on all sides shows least displacement and highest stresses along the edges of the slab. The displacement in simply supported slab on all the edges with opening is 18.02% higher than the slab without opening with same boundary condition [6].

In this research a study on simply-supported and fixed-end square slabs with opening at ultimate limit state using the yield line method was carried out and the results were presented. The results showed that, in simply-supported slabs the ultimate area load capacity decreases with the increase in size of opening up to 0.5 times the slab dimension. After which the ultimate area load capacity increases with the opening size and registered a maximum increase of 257% at an opening size of 0.9 times the slab dimension. However, when the ultimate area load capacity is converted to ultimate total load capacity, there is a continuous decrease in ultimate total load capacity with the increase in opening size. The maximum decrease is 32% with an opening size of 0.9 times the slab dimension in this study. Therefore, a simply-supported slab may have a reduction in ultimate area load of up to 11% and a reduction of ultimate total load of up to 19% [7].

The purpose of this study is to investigate the flexural behavior of reinforced concrete one way slab with opening and applying strengthening to them by using CFRP strip. Size, shape of the opening, length, and width of CFRP strip are the main parameters that are investigated in this experimental research. These openings are situated in the maximum bending zone. The strengthening of reinforced concrete one way slab with opening by CFRP strips, with two strips of length are 500mm and 700mm which represent 2.5 and 3.5 times opening side and constant strip width of 50mm (0.25 side), gave an increase in ultimate load capacity by about 37.79% and 108.72%, an decrease in service deflection by about 47.28% and 58.31%, an decrease in concrete compressive strain by about 36.83% and 48.14%, an increase in crack load by about 78.26% and 88.41% and an decrease in crack width by about 67.22% and 69.44%, respectively. And also, the strengthening of reinforced concrete one way slab with opening by CFRP strips with two strips of width are 100mm and length of 700mm, gave an increase in ultimate load capacity by about 110.17%, decrease in service deflection by about 72.66%, decrease in concrete compressive strain by about 55.57%, increase in crack load by about 295.65% and an decrease in crack width by about 100% [8].

B. Review of Literature on Alternate Strengthening Techniques:

This study introduces a technique to strengthen opening by using steel plates and steel connectors. The effect of thickness of slabs with an opening and thickness of steel plates which were used to strengthen openings on flexural strength of reinforced concrete one-way slabs were investigated and compared. The variables which were investigated in this study include: thickness of slab specimens, type of opening and thickness of steel plates which were used to strengthen openings 2, 4 and 6 mm. The test results showed that the effect of using steel plates of thickness 2 mm and 4 mm to strengthen opening was small and medium respectively, because of the yielding of steel plate, the ultimate loads for slabs with 40, 60 and 80mm thickness decrease by about 16, 10, 23% and 12, 8, 16% of the ultimate loads for slabs with the same thickness and without opening for 2mm and 4mm respectively. The effect of using steel plates of thickness 6 mm to strengthen opening was excellent, the ultimate loads for slabs 40 and 80mm thickness decreases by about 3, 8 and 3.5% of the ultimate loads for slabs with the same thickness and without opening respectively but the ultimate load for slab 60 mm thickness is about 12.5 % greater than that of slab with the same thickness and without opening. [9]

The aim of this study is to investigate the structural flexural performance of one-way slab with cut-outs. Six slabs including cut-outs contained one control un-strengthened slab along with five strengthened slab. These slabs were strengthened using either Near Surface Mounted (NSM) steel bars or Externally Bonded Carbon Fiber Reinforced Polymer (EB-CFRP) at the tension side, while four out of them were strengthened by either NSM-steel bars (one slab) or an overlay of Engineered Cementitious Composites (ECC) material (three slabs) at the compression side. The test results showed that properly designed and detailed end anchors for EB-CFRP sheets prevented the de-bonding of both ends of the sheets till the CFRP sheets ruptured around the mid-span of the slab. They enabled the CFRP sheets to utilize their full tensile capacity resulted in the full restoration of the flexural capacity of both slabs strengthened with CFRP sheets in the tension side. After the CFRP sheet ruptured, de-bonding of both CFRP sheets for both slabs were observed and extended to the end anchors locations. Among all strengthened slabs, slab that adopted NSM-steel bars along with ECC overlay technique showed the highest flexural capacity. It restored the ultimate flexural capacity of un-strengthened slab including cut-out and outperform its capacity than that of the reference slab without cut-out by about 23%. Using thin layer of ECC material of 20% the slab total thickness in the compression side ensured the full restoration of the flexural capacity due to cut-out when combined with either NSM steel bars or EB-CFRP sheets in the tension side [10].

This paper presents the results of an investigation of the monotonic and fatigue behavior of one-way and two-way reinforced concrete slabs strengthened with carbon fiber-reinforced polymer (CFRP) materials. Five one-way slab specimens were tested. Three of the slabs were retrofitted with CFRP strips bonded to their soffits and the other two served as un-retrofit, control specimens. Out of the five one-way slab specimens, one un-retrofit and two retrofit slabs were tested monotonically until failure. The remaining two specimens, one un-retrofit and one retrofit, were tested under cyclic fatigue loading until failure. In addition, six half-scale, two-way slab specimens were constructed to represent a full-scale prototype of a highway bridge deck. Of the six square slabs, two were un-retrofitted and served as the control specimens, two were retrofitted using CFRP strips bonded to their soffits making a grid pattern, and two were retrofitted with a preformed CFRP grid material bonded to their soffit. Results for one-way slab showed that*:* the monotonically tested retrofit specimens, i.e. un-cracked and cracked achieved an increase in ultimate strength of 14.8 and 18.1%, respectively, over that of the un-retrofit control specimen. The failure of the two monotonically tested retrofit slabs was due to de-bonding of the CFRP that propagated outward from the mid-span region as the applied load increased. *Results for two-way slab showed that:* For the monotonically tested slabs, the CFRP strip retrofitted slab, and the CFRP grid retrofitted slab, achieved ultimate strength increases of 13.8 and 10.7%, respectively. Specimen retrofitted with CFRP experienced an 8.7% increase in the general cracking load and Specimen retrofitted with CFRP grid experienced a 34.8% increase in the general cracking load [11].

In this paper, the results of the behavior of two-way RC flat slabs with a centered square opening are presented. Three slabs were tested to failure, consisting of a control specimen with no opening, one specimen with an opening and no strengthening, and one with an opening and three CFRP plies applied to the tension face along each side of the opening. The test results revealed that externally bonded CFRP laminates significantly increased both the overall stiffness and flexural capacity of the slabs with an opening. It shows that such positive-moment strengthening of cutout slabs is entirely viable using CFRP laminates. It also showed that anchoring the CFRP has resulted in a high capacity without premature de-bonding of the laminate, which would otherwise have occurred due to the extensive flexural cracks that developed on the tension face of the specimen [12].

In this study six specimens of similar dimensions and reinforcement details were prepared, two of which were un-strengthened and served as control specimens, while the remaining four were strengthened with two different schemes: orthogonally (Scheme 1) and diagonally (Scheme 2) bonded carbon-fiber-reinforced polymer (CFRP) laminates on the top surface of the slab. The progressive collapse performance of the strengthened specimens was studied in terms of their load-displacement relationships, first peak strength, initial stiffness, and energy dissipation capacities. The test results showed that the vulnerability of orthogonally & diagonally strengthened medium slab reinforcement was lower than that of orthogonally & diagonally strengthened low slab reinforcement because the extent of the tensile membrane action in flat slabs under the loss of a corner column. Orthogonally & diagonally strengthened low slab reinforcement could increase the dynamic ultimate strength by 74.0 and 82.0%, respectively. Moreover, orthogonally & diagonally strengthened medium slab reinforcement increased the dynamic ultimate strength by 47.9 and 52.1%, respectively [13].

This paper describes the results of experimental testing of glass fiber reinforced plastic (GFRP) composite beam strengthened reinforced concrete (RC) slabs with two symmetrical openings. The aim of this study is to investigate the most effective strengthening method using GFRP composite beams in slabs with openings for enhancing the load carrying capacity and stiffness. Test results showed that the strengthened slabs seems to increase the load carrying capacity by 29%, 21% and 12% over that of the control specimen for diagonal, parallel and surround strengthening respectively. It was also observed that the slab strengthened with GFRP composite beams failed by flexure due to the intermediate cracks and de-bonding of GFRP composite beam with a wide open crack. Also, there were no significant differences in crack patterns and the extent of cracks between different strengthening types in this study [14].

This paper reports field tests on the use of Carbon Fiber Reinforced Polymers (CFRP) strengthening and steel fiber to restore the load capacity of the slab after having openings cut-out in the positive moment region. Eight slabs were casted to evaluate the ability of the CFRP strengthening and steel fiber to restore the load capacity of the slab, made of self compacting concrete, after introducing the openings. Two different strengthening techniques were investigated to determine the most effective system for strengthening. The two different strengthening techniques are the use of externally bonded CFRP strips, and add steel fiber 1% by volume fraction. The test results showed that use of steel fiber increased the load capacity by 26.67% and 9.83% for small and large opening respectively and the use of CFRP increased the load capacity by 46.67% and 55.7% for small and large opening respectively [15].

In this paper, laboratory tests on 11 slabs with openings, loaded with a distributed load are presented together with analytical and numerical evaluations. Six slabs with openings have been strengthened with carbon fibre reinforced polymers (CFRPs) sheets. These slabs are compared with traditionally steel reinforced slabs, both with (four slabs) and without openings (one slab). The work presented in this paper shows that CFRP sheets can be used to maintain and even increase the original load-capacity of two-way concrete slabs with openings. For the CFRP strengthened slabs, the load carrying capacity was increased with 24–125% in comparison to respective weakened slab, and with 22–110% in comparison to the homogeneous slab. The results also showed that the slabs with the larger openings have a noticeable higher load carrying capacity and a stiffer load–deflection response than the slabs with the smaller openings [16].

This paper shows the results of tests on 10 FRP-strengthened RC slabs anchored with FRP anchors of varying geometry and positioning. Optimal arrangements of anchors in these tests have enabled the load and deflection capacities of the FRP-strengthened slabs, in relation to the unanchored but strengthened control slab, to be enhanced by up to 44% and 216%, respectively. Strain utilization of the FRP plate has also been shown to increase from 44% of the flat coupon strain capacity for the unanchored but strengthened control slab to 95% for an optimally anchored FRP-strengthened slab [17].

The purpose of this study is to investigate flexural behavior of one way RC slab with opening and applying strengthening to them by using CFRP strips. Size and location of opening on the slab are the main parameters that are investigated in this experimental research. Three different square opening with 300 mm, 400 mm and 500 mm side are tested. These openings are situated in two different places, bending and shear zone. Two series of test are done during experimental program. First set of experiments are done without strengthening and second set of test are done after strengthening with CFRP strips. Totally, thirteen test specimens are tested, including one reference specimen, six specimens without strengthening and six specimens with strengthening. CFRP strips are located around the openings along the specimen. The test results showed that maximum load carrying capacity and the yield stiffness of the specimens are improved by the application of strengthening technique. Average increases in load carrying capacity are turned out to be 1.16 and 1.48 times for the specimens at which shear and flexural fractures are observed, respectively. Average increase in load carrying capacity is calculated as 1.32 times, when all strengthened specimens are taken into account. Average increases in yield stiffness are turned out to be 1.05 and 1.22 times for the specimens at which shear and flexural fractures are observed, respectively. Average increase in yield stiffness is calculated as 1.14 times, when all strengthened specimens are taken into account [18].

This paper presents an experimental and analytical investigation for evaluating the ultimate response of unreinforced and reinforced concrete slabs repaired and retrofitted with fiber reinforced polymer (FRP) composite strips. A uniformly distributed pressure was applied to several two-way large-scale slab specimens using a high-pressure water bag. The test results indicated that both FRP systems were effective in appreciably increasing the strength of the repaired slabs to approximately five times that of the as-built slabs. For retrofitting applications, use of FRP systems resulted in appreciable upgrade of the structural capacity of the as-built slabs up to 500% for unreinforced specimens and 200% for steel reinforced specimens [19].

In the present work, the combined strengthening strategy, a Steel fibre-reinforced concrete (SFRC) overlay and NSM CFRP laminates, was applied to significantly increase the flexural resistance of existing RC slabs. The test results showed that the hybrid strengthening technique has great potential application towards flexural strengthening of RC slabs, not only in terms of increasing the slab ultimate load capacity, but also its stiffness. The slabs strengthened by the NSM technique and SFRC presented an increase of approximately 244% in the service load with respect to that of the reference slabs. Compared to the NSM technique, the hybrid strengthening strategy led to an increase of about 122% in the load at the deflection serviceability limit state. The hybrid strengthening system also led to an increase of about 350% in the RC slab maximum load carrying capacity with respect to that of the reference slabs, and an increase of about 80% in comparison to that of the slabs only strengthened with the NSM technique [20].

This paper presents the results of experimental investigations on reinforced concrete slabs strengthened using fibre-reinforced polymers (FRP). Investigations on slabs with cut-outs revealed that the FRP can be placed only around the edges of the cut-out when retrofitting the slabs whereas, in the situation of inserting cut-outs combined with increased demands of capacity, it is necessary to apply FRP components on most of the soffit of the slab. The tests showed that the load capacity of slabs with cut-out openings is not directly proportional to the reduction in their area. Reducing the effective area of a solid slab, by cutting out small and large openings, to 87% and 75% can decrease the resistance to 73%, 63% and 57% respectively. The proposed strengthening system enabled the load and deflection capacities of the FRP-strengthened slabs, in relation to their un-strengthened reference slabs, to be enhanced by up to 121% and 57% for slabs with and without cut-outs respectively [21].

In this paper the use of mechanically-anchored un-bonded fibre reinforced polymer (MA-UFRP) system is used to upgrade reinforced concrete (RC) slabs deficient in flexural strength. A total of six RC slabs, were constructed and tested to failure under four-point bending. One slab was used as a control slab while the other five slabs were strengthened with various fibre reinforced polymer (FRP) strengthening systems, each having 0.12% external FRP reinforcement ratio. Two slabs were strengthened with externally-bonded FRP (EB-FRP) system, one slab with end-anchorage and one slab without end-anchorage. The remaining three slabs were strengthened with MA-UFRP system having various anchors' locations. The test results showed that EB-FRP strengthening system without end-anchorage increased the yield and the ultimate loads by about 38% and 46%, respectively relative to those of the control. The slab failed prematurely by delamination of the CFRP strip. The presence of end-anchorage in the EB-FRP system prevented delamination of the CFRP strip which slightly increased the slab strength but greatly improved the slab deflection at ultimate load. The ultimate load of the slab strengthened with EB-FRP with end-anchorage was about 62% higher than that of the control slab. MA-UFRP strengthening system resulted in only 33% average strength gain relative to that of the control with a minimum and a maximum of 20% and 43%, respectively. The slab mid-span deflection at ultimate load was lower by 45%, 19%, and 15% compared with that of the control slab for EB-FRP system without end-anchorage, EB-FRP system with end-anchorage and MA-UFRP system respectively [22].

In this paper a series of tests on one-way spanning simply supported RC slabs which have been strengthened in flexure with tension face bonded FRP composites and anchored with different arrangements of FRP anchors are conducted. The load–deflection responses of all slab tests are plotted, in addition to selected strain results. The behaviours of the specimens including the failure modes are also discussed. The test results showed that the increase in strength and deflection recorded, over the unanchored but strengthened control counterparts, was 30% and 110%, respectively. In addition, the usable strain in the FRP plates was increased from 45% of the capacity of unanchored but strengthened control slab to almost 80% of optimally designed anchorage schemes. Anchors positioned in the shear span were found to be most effective. Closer spaced anchors were found to reduce the rate of debonding crack propagation and also enabled higher deflections to be achieved. Anchors spaced far apart led to gains in deflection capacity but limited gains in strength [23].

In this paper a study on the flexural behavior of two-way reinforced concrete slabs externally strengthened with Pre-stressed or non-pre-stressed carbon fiber-reinforced polymer CFRP sheets is being carried out. Four large-scale flat plate slabs are tested and a nonlinear three-dimensional finite-element analysis is conducted to predict the flexural behaviors of the tested slabs, including the load-deflection response, strain distribution, crack propagation, and crack mouth opening displacement. The test results conclude that an increase in the flexural load-carrying capacities of up to 25% and 72% (32% and 80% in the FEA) was achieved for the slab strengthened with non-pre-stressed and pre-stressed CFRP sheets, respectively, as compared to the unstrengthened control slab. Failure of the control slab was very ductile; on the other hand, step-wise failure was observed in the strengthened slabs because of the delamination or partial rupture of the CFRP sheets. Typical orthogonal and diagonal crack propagations were observed in the tested slabs [24].

In this paper the feasibility of strengthening concrete slabs in flexure, with and without cutouts, using the mechanically fastened (MF FRP) technique is investigated. Two series of large-scale reinforced concrete slabs are tested. The first series is comprised of five slabs without a cut-out, and the second series consists of four slabs of the same dimensions with a central cutout. The mechanically fastened system is found to be a valid alternative to the externally bonded system resulting in a rapid, economic, and effective strengthening technique for two-way concrete slabs. The test results showed that for slabs without cutouts, increase in the yield and ultimate load of about 30% and 66%, respectively, were observed. For slabs with cutouts, the strengthened specimens showed increase up to 17%, 10%, and 33% in the crack, yield, and ultimate loads, respectively, over the corresponding control specimen [25].

This study was undertaken to note down the effect of the main steel corrosion on the structural performance of RC slabs strengthened with carbon-fiber-reinforced polymer (CFRP) strips and exposed to a corrosive environment. A total of eight specimens were constructed and tested under monotonic static loading. Three specimens were CFRP-strengthened and corroded, three specimens were CFRP-strengthened and kept at room temperature, one specimen was unstrengthened and corroded, and one specimen was neither strengthened nor corroded. Three different strengthening schemes were applied: (1) externally bonded CFRP strips; (2) externally bonded CFRP strips provided with CFRP anchors; and (3) near surface mounted (NSM) CFRP strips. The experimental results showed that the increase in flexural capacity achieved using the three strengthening schemes were significantly reduced due to corrosion of the main steel. The results showed that the reductions in flexural strength gains for the CFRP-strengthened corroded slabs relative to the gains for the strengthened un-corroded slabs were about 55%, 38%, and 41% for the externally bonded CFRP system without anchors, externally bonded CFRP with anchors, and NSM-CFRP system, respectively [26].

This paper presents the test results of reinforced concrete slabs strengthened with pre-stressed and gradually anchored carbon fiber–reinforced polymer (CFRP) strips under monotonic and cyclic loading. To take full advantage of the externally bonded CFRP technique, it is beneficial to apply the laminates in a pre-stressed state, which relieves the stress in the steel reinforcement and reduces crack widths and deflection. The cyclic tests were performed to identify the fatigue behavior of the strengthened slabs and to investigate the influence of long-term cyclic loading and elevated temperature on the bond properties of the pre-stressed CFRP laminates and the ductility and flexural strength of the strengthened slabs. The slabs tested monotonically showed a considerable increase in the cracking load and the ultimate load of the elements strengthened with the pre-stressed strips [27].

This paper reports the results of an experimental program to investigate the bonding behavior of two different types of fiber-reinforced polymer (FRP) systems for strengthening RC members: externally bonded carbon

(EBR) plates and bars or strips externally applied with the near-surface-mounted (NSM) technique. The overall experimental program consisted of 18 bond tests on concrete specimens strengthened with EBR carbon plates and 24 bond tests on concrete specimens strengthened with NSM systems. The test results showed that the tensile strength of the FRP materials is better exploited by the NSM technique with much higher utilization factors (36–100%) than those attained in EBR systems (approximately 15%). This indicates that the NSM strengthening technique may represent an interesting alternative to EBR plates. The NSM technique also allows higher efficiency factors to be attained against lower axial stiffness, especially if the reinforcement surface is ribbed [28].

V. CONCLUSION

1) Based on the previous studies and the above literature review the following conclusions can be made:
2) EB-FRP laminates increases the flexural strength of slab with cut-outs and it also enhances its stiffness.
3) FRP sheets are more effective in strengthening systems as compared to FRP strips as there is premature de-bonding failure due to higher stiffness in FRP strips.
4) FRP sheets increase the load carrying capacity of slab with opening by applying different positioning of FRP sheets.
5) The cracking pattern found in the opening shows a high concentration of stress being occurred at the corner of the opening when vertical load is applied.

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