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Review On Crack Repair And Strengthening Techniques In Concrete Slabs

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ABSTRACT
One of the most observed and frequent defections in reinforced concrete slabs is the appearance of cracks, which created due to factors like reinforcement corrosion, overloading, and differential settlement of supports. Strengthening and retrofitting are needed to restore the structural capacity of the distressed elements. There are different techniques available for retrofitting and strengthening of various reinforced concrete structural elements. The current study introduces and discusses five different approaches of repairing cracks and strengthening in concrete slabs that are available and used nowadays, namely; CFRP (Carbon Fibre Reinforced Polymer), Applying ferrocement layer, cement grout, section enlargement, and epoxy injection. Each method discussed briefly, and the properties and procedures of each technique are explained. The efficiency of each method is discussed in accordance with the others through reviewing studies and conducting a comparison between the mentioned approaches and evaluating the results. An investigation reviewed in which all five methods are applied on the cast and cracked slab samples with identical compressive strength and reinforcement and compared with the control slab, which was an intact one. The slabs loaded to the failure stage, and after the creation of cracks, each sample repaired using one of the methods. Failure modes, concrete and steel strain variation, and the collapse loads of the examples were measured, evaluated, and compared. It observed that the load-carrying capacity of the repaired samples differs majorly according to the type of repair technique used, which redistributed the strains and stresses in both concrete and steel reinforcement. All methods of slab repair resulted in restoring or enhancing the structural capacity of cracked concrete slabs.
KEYWORDS *CFRP, Epoxy injection, Ferrocement, Repairing, and strengthening*

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I. INTRODUCTION

1.1 Background

Cracks in concrete have many causes. They might only influence the appearance, or might be signs of more essential and significant structural problems or a lack of durability. Cracks might exhibit the total depth of the problem and the damage extent, or they might indicate more significant issues. The nature of the crack and the type of structure suggests the significance of the problem [1].

Insufficient maintenance, excessive loading conditions, change in the function of the structure, and exposure to severe environmental conditions lead to the necessity of strengthening and repair in reinforced concrete (R.C.) structures. Reduction in the alkalinity of concrete is one of the significant causes of deterioration, which leads to oxidation of the reinforcing steel. The oxidation process is one of the most common reasons for concrete cracks spalling. Steel plate bonding, external prestressing, and reinforced concrete jacketing are among the several strengthening techniques that were popularly developed and used in the past. These techniques increase the load-carrying capacity of the elements effectively; however, they are susceptible to corrosion damage that leads to failure of the strengthening system. As a result, innovative non-corrosive strengthening systems are required to replace the old strengthening systems with potential for increasing service lives of reinforced concrete structures and reduction in costs of maintenance [2].

1.2 Necessity of R.C. slabs Strengthening

To consider the necessity of strengthening reinforced concrete members, the situations in which existing concrete structures or some of their components may found to be inadequate and in need of repair or strengthening must analysed. The following are the situations in which intervention required to repair or strengthen reinforced concrete slabs [3]:

a) Restoring strength and stiffness of deteriorated or damaged concrete slabs.

b) Corrosion of the reinforcement.
c) Preventing crack width increase and dilation under sustained or increased loads.
d) Retrofitting concrete elements and enhancing the strain to failure and flexural strength of concrete members affected by high loading conditions as in traffic loads or earthquakes.
e) Construction and design defects correction, as in undersized reinforcement.
f) Increasing and improving the reinforced concrete slabs service life.
g) It was applied shear strengthening around columns when the parameter is not sufficient to undertake the punching shear.
h) The structural system varied as in cut-outs in the existing reinforced concrete slabs.
i) Design parameter variations.
j) Structure optimization is concerning the reduction in stresses in rebar and deformations.

The rebar becomes oxidized due to the alkalinity reduction of the concrete. It leads to the initiation of premature cracks, which results in strength reduction, decreasing stiffness, and shorten the service life, and finally, failure in concrete, which may ultimately lead to structural failure. Concrete structures become weak due to the tension caused by the expansion of corroded steel as a result of rebar corrosion. Rehabilitation requires restoring stiffness and strength of concrete members that are affected by corrosion of reinforcement [2]. Bridges, as one of the concrete structures, are damaged more frequently because of being susceptible to harsh environmental conditions [4].

Proper crack repair is dependent upon recognizing the causes and selection of repair approaches that are the best to overcome these causes; otherwise, the failures will be recurrent. A repair procedure considered successful only if it eliminates or can resist the cause of crack creation as well as the cracks themselves. [2]. After precise evaluation of the cracks' cause and the extent of them, approaches may take to restore and increase strength and stiffness, to improve functional performance, provide water tightness, improve the appearance of the concrete surface, improve durability and prevent the development of a corrosive environment [1].

To strengthen a structure or part of it and to restore its strength and serviceability, a variety of repair approaches developed. It is also prudent to consider the durability aspect when repair or strengthening carried out. With the advancement of new materials technology, which has superior mechanical properties and high resistance to electrochemical corrosion, many effective strengthening and repair techniques developed. The factors indicating the ultimate selection of the most effective and suitable approaches for repair are application speed, simplicity, structural performance, and overall cost [4].

The current study investigates five methods of crack repair in concrete slabs along with conducting a comparison between the results of applying each type of retrofitting on the structural response of repaired slabs in terms of serviceability, ductility and finally strength performance for each type of the repair techniques to evaluate their potential application in cracked reinforced concrete slabs.

The repair methods are as followed:
a) Carbon Fibre Reinforced Polymers (CFRP).
b) Cement grout.
c) Epoxy injection.
d) Ferrocement cover.
e) Section enlargement.

These techniques were selected for their potential either to increase the structural capacity of members or to re-establish the sections' original function.

1.3. Aims and Objectives

The objective of the current study is to conduct a review of the current methods of repairing cracks in concrete slabs and comparing the effect of applying them on their mechanical properties and evaluating along with analyzing the efficiency of each technique.

II. METHODS OF CRACK REPAIR AND STRENGTHENING IN CONCRETE SLABS

2.1Repair and Strengthening Using CFRP

Composite materials have accepted among civil engineers. In particular, fiber-reinforced polymers (FRP) are becoming a viable choice for reinforcing and rehabilitating damaged structures. Extensive research across the world during the last three decades has resulted in a better understanding of the properties and the behavior of FRPs under various conditions. Nowadays, carbon fiber- reinforced polymers (CFRP) are commonly used as external reinforcements to increase the flexural strength of existing cracked Reinforced Concrete (R.C.) members. Their competitive properties are the high tensile strength to the weight ratio, water-resistance, and ability to limit cracking tendency [5].

FRPs are composites made of high strength fibers permanently, bonded by a continuous resin or polymer matrix. Of the commercially available fibers, three glass (GFRP), aramid (AFRP), and carbon (CFRP) have the necessary combination of strength and stiffness needed to replace steel. FRP products can form into grids, sheets, rods, and winding strands. Fibers make up between 40 and 70% of the volume and are the principal load-carrying elements. On the other hand, the polymer matrix acts as a medium for load transfer and protects fibers from environmental damage. Recent research and experiments related to the composite material used for retrofitting existing bridges have shown that this method is more cost-effective and requires less effort and time than traditional methods Figures 1, 2 and 3 [6]. Composite materials offer unique advantages in solving many practical problems in areas where conventional materials fail to provide satisfactory service life. Unlike steel, composites claimed to have better corrosion-resistant properties [7].

Studies have shown that fiber-reinforced plates (FRP) increase the strength of flexural members significantly. CFRP has a high strength to weight ratio, desirable fatigue behavior, and excellent resistance to electrochemical corrosion, which makes it a practical approach [9]. In a study conducted by Alfarabi et al., 1994 [10], it was observed that even though using FRP leads to an increase in the failure loads, most of the beams that were strengthened by FRP started to fail at the plates' curtailment zones. The epoxy used to install the plate under flexural members failed at loads that were much higher than the required level [11]. A similar study also found that the failure modes for repaired structures might vary from ductile to brittle [12].

Figure 1. Strengthening and repair of bridges using CRFP laminates [8]

Figure 2. Strengthening and repair of bridges using CRFP laminates [8]

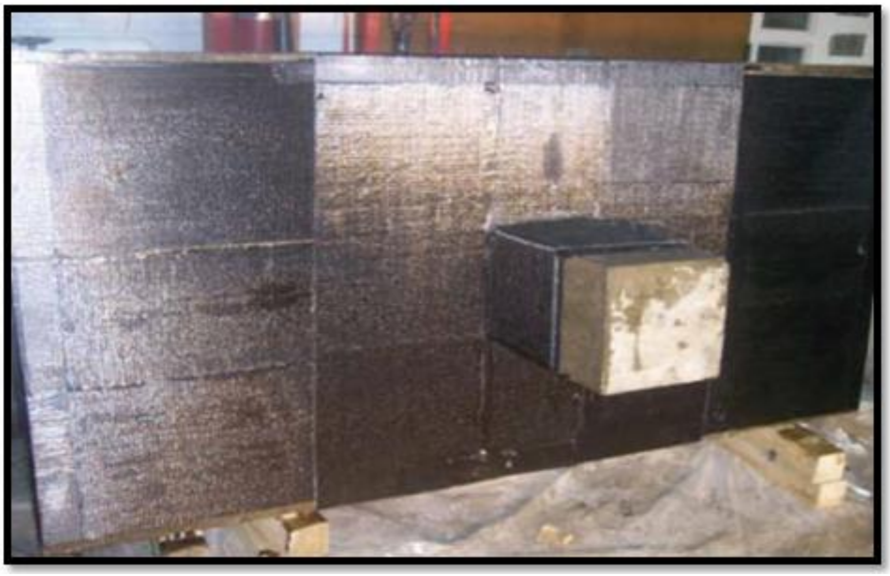

Figure 3. Flat slab specimen rehabilitated with CFRP prepared to be tested [5]

The possibility of this variation is dependent upon the FRP location, percentage of used FRP, and the shear rebar presence in the structures. Toong and Li [13] investigated the effect of using (CFRP) plates in strengthening one-way slabs to increase the flexural capacity with a significant focus on the cracking behavior at the working load. A substantial increase in load-carrying capacity observed in all the CFRP strengthened specimens with a range of 60% - 140%.

2.2Repair and Strengthening Using Ferrocement

Ferrocement is a type of thin composite material made of cement mortar reinforced with uniformly distributed layers of continuous, relatively small diameter wire meshes. The wire meshes evenly distributed in endless layers with relatively small diameters [2]. Romualdi [14] and Iron [15] in the early 1980s introduced the usage of ferrocement in concrete repair for the first time mainly as membranes for the restoration of liquid retaining structures, such as pools, sewer lines, tunnels, etc. Investigation in the usage of ferrocement as strengthening components for strengthening and repair of R.C. beams reviewed by Paramasivam et al. [16]. In general, the damaged concrete and/or reinforcement were removed and replaced with ferrocement, with or without any changes in overall dimensions of the beam. The beams tested under static or cyclic loading conditions [14]. The strengthened beams reported exhibiting improved cracking resistance, flexural stiffness, and ultimate loads in comparison with the original beams. These improvements, however, are dependent upon the full composite action in between the layers of ferrocement. Al-Kubaisy and Zamin [17] demonstrated the flexural behavior of R.C. slabs strengthened with a cover of ferrocement in the tension zone. Twelve simply supported (500 mm2) reinforced concrete slabs tested under flexural load. They considered the effect of factors like ferrocement layer thickness, wire mesh percentage in the ferrocement layer, and the connection type between the R.C. slab and the ferrocement layer, on the first crack load, ultimate flexural load, the width of cracks, spacing and relationship between load and deflection.

For applying this technique, first, the concrete from the cracked zone is removed using hammer and concrete chisel or mechanical hammering instruments. Then, a layer of skeletal steel and a layer of galvanized welded wire mesh fixed with the original reinforcement of the slab Figures4 and 5. The concrete surface must roughen before placing the additional reinforcement.

Technological restrictions and design indicate the dimensions of the extra reinforcement. Finally, the cement mortar is applied and left to cure for 28 days.

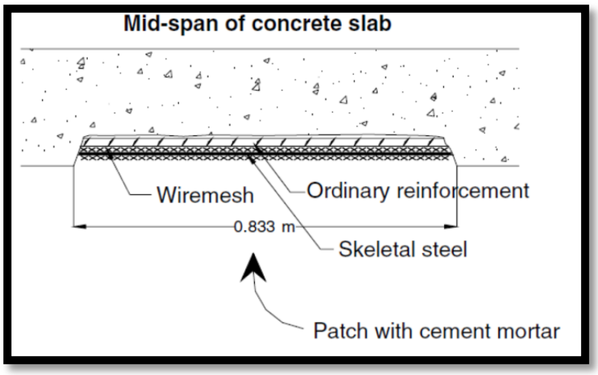

Figure 4.Ferrocement layer technique [2]

Figure 5. Wired mesh used for repair [2]

2.3 Repair and Strengthening Using Cement Grout

In the grout pouring technique, the existing reinforcement has to expose through enlarging the existing cracks, both in-depth and width. The extended cracks must clean before pouring the grout. It can do using compressed air, water jet, or a simple steel brush. Figures 6 and 7 show the approach of the technique proposed by Waleed A. Thanoon et al. [4] in a study over the effects of different repair techniques on the structural response of one way reinforced concrete slabs. The grout used in the experiment was a non-shrink premixed high strength cement grout [2].

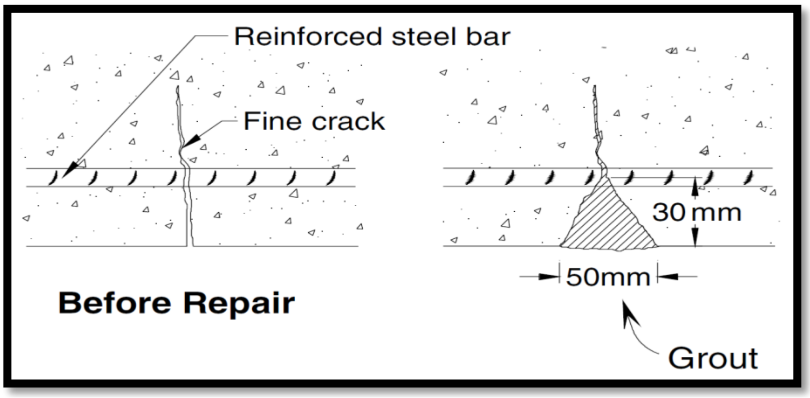

Figure 6. Grout pouring technique [4]

Figure 7. Cracks repaired using grout pouring technique [4]

2.4Repair and Strengthening Using Section Enlargement

In section enlargement, an R.C. jacket applied around the distressed member to achieve desired section performance and properties. An increase in size of the concrete section after jacketing and requirement for formwork construction are the main disadvantages of this approach. Section enlargement increases the capacity of carrying loads and stiffness of the slabs. The typical thickness of expansion ranges from 5-8 cm for slabs. The strengthening by section enlargement can perform in two ways [18]:

a) Strengthening through adding the new R.C. layer under the structural member.

b) Strengthening through adding the new R.C. layer on top of the structural member.

The most critical issue to consider in this approach is to make sure that the bond between the old concrete and the new one is strong. Particularly the shrinkage properties of the layers must take into careful consideration. Applying a new R.C. layer on top of the slab is considered to be much more comfortable. It observed from experience that in lots of cases, it is a necessity to apply the new R.C. layer on the lower face of the member, especially in the zones of decisive bending moments. The bottom face of the slabs can be cast using particular types of formwork or concrete or using shotcrete.

This method comprised of the following stages:

First, the deteriorated concrete and the corroded layers of original slab steel bars have to remove, and the surface should clean to ensure proper and strong bonding between the slab and the repairing material. Additional reinforcement is added or replaced and, in some cases reinforcement protection, and then the repair material is applied. Figures8 and 9 show the approach and results of this technique used by Waleed A. Thanoon et al. [4]. It is a traditional strengthening approach. The material costs are relatively low, but the cost and consumption of the labor are rather high [2].

Figure 8. Roughened surface and steel provided and prepared for casting the extra 5cm layer of concrete [2,4]

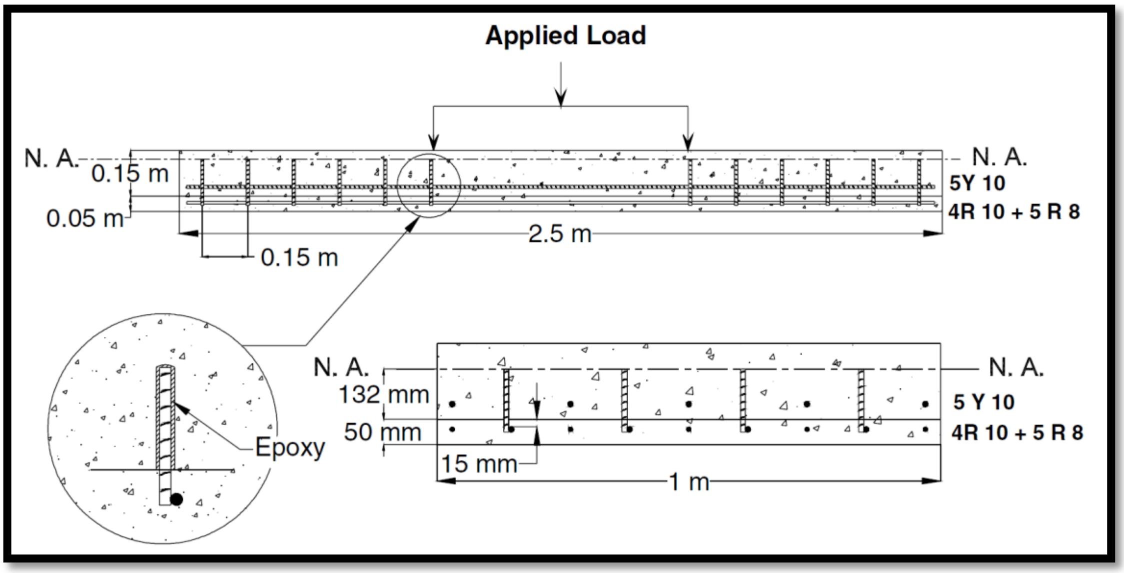

Figure 1.Section enlargement technique [4]

2.5Repair and Strengthening Using Epoxy Resin Injection

Epoxy Injection is one of the most extensively tested and widely used methods of repairing cracks in concrete structures. This repair method is disruptive minimally, and it is cost-effective, as it does not require replacement of the concrete.

2.5.1 Advantages of Epoxy as a repair material

Several causes make epoxy, a very suitable material to be used with concrete. Among them are [19]:

- **Adhesion**

Epoxy's excellent adhesive property allows it to create a strong bond to almost all construction materials.

- **Versatility**

Epoxy resin systems are considered widely in most of the repair situations, including coating, repair overlay, and strengthening due to their wide range of available physical and chemical properties. Epoxy can be used for a variety of applications due to the diversity of diluents, curing agents, fillers, extenders, and other modifications that are available to the formulator.

- **Chemical resistance**

Epoxies exhibit good resistance to acids and alkalis, oils, and solvents.

- **Low shrinkage**

Compared to other thermosetting resins, epoxies observed to have low autogenous shrinkage. There are formulations in which effective linear shrinkage is as low as 0.001 percent.

- **Rapid hardening**

At normal ambient temperatures, it is very probable for a mixture of resin and hardener system to solidify in merely several minutes. This amount of time can prolong for several hours by changing the applied system.

- **Moisture resistance**

Epoxy is a very impermeable material to the extent that a thin layer of it can provide a high degree of water insulation even if it is submerged continuously in it. However, some types of epoxy materials have lower permeability degrees and may absorb water in humid environments, so care must provide when choosing epoxy products that have low water absorption. If the material has less than 1 percent absorption as measured by ASTM D 570 and specified by ASTM C 881 then water absorption would not make problems.

2.5.2 Important precautions to consider while using epoxy resin

Although epoxy resin has remarkable benefits, they should deal with, with caution. Some necessary precautions summarized in the following discussion:

- **Strain compatibility**

The creation of a bond between epoxy and the concrete surface happens rapidly, and the two materials may consider as one within a short time. The self-generated shrinkage strains that happen during curing in some epoxy formulations might lead to severe strains at the bond line. It may result in delamination when combined with thermal strains, which generally fail at the top (6 mm) of the interface of concrete.

There is a wide difference in thermal expansion coefficients between the cured epoxy layer and the concrete. Even normal temperature variations can be the cause of delamination. Filling the epoxy system with fillers such as silica reduces the difference in thermal expansion in proportion to the amount used. The system can be adjusted for the difference in the thermal coefficient of expansion if a flexible epoxy compound is used [19, 20].

- **Thermosetting plastic**

The components of the epoxy system must mix perfectly, and the temperature must control carefully both before and during stages of mixing and curing. In selecting the epoxy formulation, care should take to select the type that works properly in the given temperature of repaired condition. Not all epoxies work well on a cold substrate, for instance. Specifications for three temperature cure classes can find in ASTM C 881. The epoxy will not melt once it is applied, and the repair has done. However, many systems lose some of their elasticity at higher temperatures and become cheesy since their mechanical properties change significantly beyond their heat deflection temperature (HDT). The HDT differs according to different types of formulations, but for the systems that applied in construction, it usually has a range between 60 to 160° F (15 to 71° C) [19, 20].

- **Slabs on grade**

Slabs on grade can present unique bonding problems if moisture is present in or under the slab while applying epoxy material on the slab. Sometimes due to the capillary action of water, the slab surface becomes moist, which may exert forces on the epoxy material and weakens the bond. Even if moisture is not present during application and cure, these same forces can subsequently cause loss of a bond that was weak because of other factors such as inadequate surface preparation [19, 20].

- **Safety :**

Epoxy compounds must handle and dealt with safely as they may cause allergic reactions. It is imperative to handle the equipment used in applying epoxy carefully, as they often need more caution than the material itself. [19, 20].

2.5.3 Steps of applying Epoxy Resin Injection

Epoxy injection requires a high degree of skill for satisfactory execution, and the application of the technique may be limited by the ambient temperature. The general procedures involved in epoxy injection are as follows:

2.5.3.1 Clean the cracks

First, the cracks should clean from any kind of contaminations as in dirt, soil, grease, or concrete residue as they create a barrier that prevents proper bonding. Cleaning is preferred to do by vacuuming or flushing with water or other effective cleaning solutions, and then flush out the solution using a neutralizing agent and compressed air [20].

2.5.3.2 Seal the surfaces

To keep the epoxy from leaking out before gelling, the surface of the cracks should seal first. A 13mm deep and 20mm wide V-shape cut out can be made in the crack if there is a need for extremely high injection pressure [19, 20].

2.5.3.3 Install the entry and venting ports

Three methods are generally used to install the epoxy entry points:

i-Fittings inserted into drilled holes:

It is the first method used to inject epoxy. It usually accompanied by V-grooving of the cracks. In this method, a hole with a diameter of 20mm is drilled into the crack about 25mm below the tip of the V-grooved section. A fitting as in tire valve stem or a pipe nipple installed with an epoxy adhesive. To prevent the cracks from being clogged with drilling dust, a water-cooled core bit or a vacuum chuck and the bit can be used.

ii-Bonded flush-fitting:

Another method to provide an entry port when the cracks are not V-grooved is to install a fitting flush on the face of concrete over the crack. The flush fitting has a flange at the bottom that is bonded to the concrete and an opening at the top for the adhesive to enter, as shown in Figures10 and 11.

Figure 10 Injecting epoxy into the cracks through the fitting [23]

Figure 11.Bonded Flush fitting [23]

iii-Interruption in seal
Omitting the seal from a part of the crack is another system of injecting the epoxy. This method used if special gasket instruments are available that can cover the unsealed portion of the crack and allow adhesive injection into the crack directly with no leakage.
iv-Mix the epoxy
Epoxy mixing is applied by batching or using a continuous mixing method.
Based on the instructions of the manufacturer, in batch mixing, a premix of the adhesive components is prepared using a mechanical stirrer.
In a continuous mixing system, the two liquid adhesive components pass through an automatic mixing head after passing through metering and driving pumps. In this system, fast setting adhesives can use that have a short working life.
v-Inject the epoxy
Devices like air-actuated caulking guns, hydraulic pumps, or paint pressure pots can use to inject the epoxy into the cracks. Careful consideration must apply in choosing the injection pressure. Higher levels of injection pressure often do not result in higher rates of injection. On the contrary, using too much pressure can cause further damage by enlarging the existing cracks. Figures12 and 13 show an injection of epoxy resin into a 1/16 and ¼ inch cracks, respectively in two different slab specimens [19, 20, 21].

Figure 12. Automatic metering, mixing and dispensing device used in a <1/16-inch crack slab specimen [21]

Figure 13. Caulk gun used to manually dispense the epoxy mixture in a 1/4-inch crack slab specimen [21]

vi-Remove the surface seal: The surface seal can clear away after proper curing of the injected epoxy by grinding or other appropriate approaches.

III. COMPARISON BETWEEN THE FIVE APPROACHES OF CRACK REPAIR IN SLABS

3.1 Applied investigation procedure

In a study conducted by Thanoon et al., 2005 [4], all five mentioned methods of repairing cracks were implemented and tested on different specimens of reinforced concrete one-way slabs. The structural behavior of the repaired slabs investigated, evaluated, and compared.

After loading the slabs until failure, structural response of the slabs specimens as in ultimate collapse loads, deflection and strain variation in concrete and steel observed. The type of repair technique found to affect the capacity of load-carrying of the slab and kind of stress and strain redistribution in both concrete and the steel reinforcement [4].

They cast, cured, and tested six full scales 2.5 m long x 1.0 m wide and 0.15 m thick one-way R.C. slabs with steel reinforcement of five 10 mm diameter high-yield deformed steel bars with a tensile strength of 460 MPa. The casted concrete had a 28-day cube compressive strength of 30 MPa. All specimens tested under a two-line load located in the mid-third section of the slab specimens, as shown in Figure14. Aside from the control slab, which loaded until failure, all slabs were loaded to two-third of their estimated ultimate load capacity or after observing crack development in the specimens (initial load ranged between 34 and 40 K.N.) [4].

Figure 14. Test set up for the slabs [4]

Each technique, the cracked slabs were repaired. After curing the fixed specimens for proper periods, each specimen was tested for ultimate load, cracking load, stiffness, and deflection, and the results were recorded and compared [4].

The sample slabs were as followed:

S1: Control slab

S2: Grout poured slab: SikaGrout214 of a density of 2.2 kg/L used to repair two 0.88mm flexural cracks at 34 K.N. [4].

S3: Epoxy injected slab.Sikadur52 was used, which is a low viscosity, free-flowing, and fast curing injection resin for filling two 0.65mm flexural cracks at 37.4 KN [4].

S4: Ferrocement repaired slab: 30 mm depth concrete from the bottom at the middle third portion of the slab was removed (with dimensions of 850 mm · 850 mm) using a chisel and hammer as shown in Figure (5). Two layers of 12.5 mm2 opening galvanized welded wire mesh of 1.25 mm diameter and a skeletal steel layer (5R6) were fixed and Cement mortar (cement to sand ratio is 1:2 with w/c ratio equal to 0.5) was applied and cured for 28 days to repair 65mm crack at 37.4 KN [4].

S5: CFRP repaired slab: In order to repair a 0.6mm crack created at 34 K.N., a 50 mm wide and 2 m long CFRP strip having 1.2 mm thickness with a tensile strength of 2800 N/mm^2, a modulus of elasticity of 165,000 N/mm^2 and a density is 1.5 kg/L were externally bonded to the tension side of the R.C. slab using Sikadur30 epoxy adhesive (bonding agent) on the central part of the slab as shown in Figures 15 and 16 [4].

Figure 3.Crack pattern before repair [4]

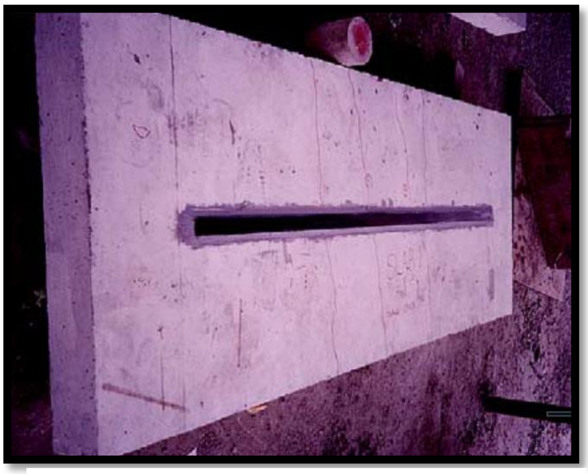

Figure 2CFRP laminate in a position [5]

S6: Section Enlargement repaired slab.
50mm thick, R.C. layer similar to the slab concrete cast on the bottom of the cracked slab. With a designed failure load of 104 KN. Forty-eight pieces of R10 steel bars of 155 mm long inserted in the holes, which as shear connectors and Additional flexural steel reinforcement 5R10 and 5R8 was next fixed to the shear connectors as shown in Figure8 [4].

3.2 Results and discussions

3.2.1 Cracking and ultimate loads

The initial cracking loads for different reinforced concrete slab specimens shown in Figure 17.

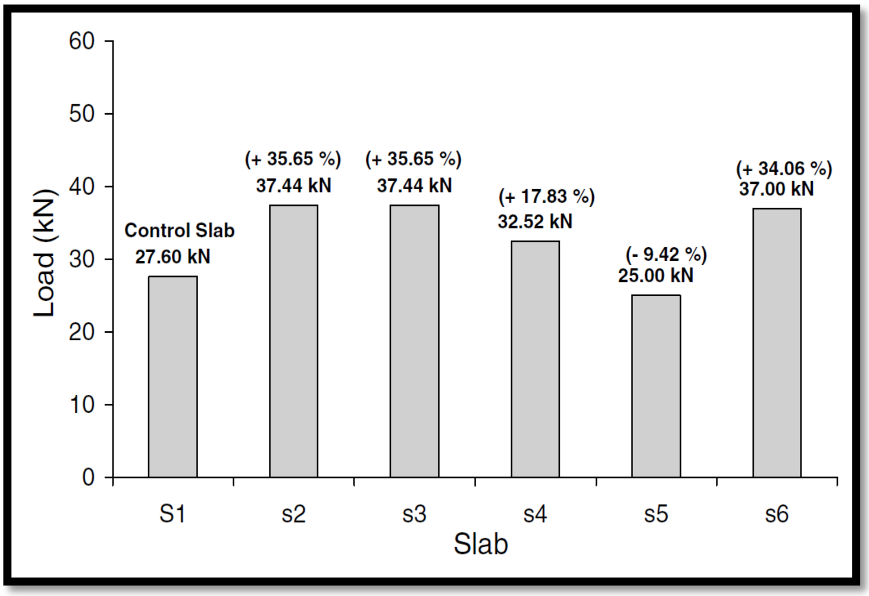

Figure 17. Cracking loads for slabs 1–6 [4]

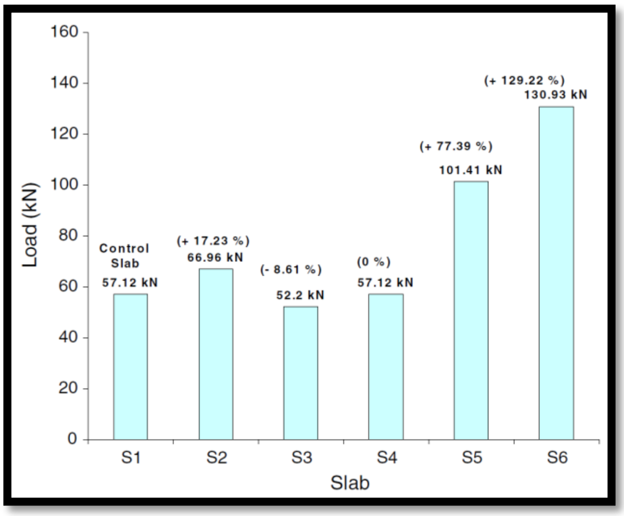

Figure 18. Ultimate loads for slabs 1–6 [4]

All repaired concrete slabs except S5 show a higher cracking load in comparison with the control slab. The strengthening of the slab by using the CFRP, without restoring the initial cracks, can only improve the crack width. In this specimen, the development of new cracks occurs at a lower load in comparison with the original slab. Figure 18 shows the ultimate failure loads for all the slab specimens [4].

It could observe that aside from specimen S3, which represents epoxy injection repair, all the repair techniques used, were able to restore the defected slabs' ultimate capacity. However, there is only an 8.6% reduction in ultimate load for S3 in comparison with the control slab. Slabs repaired by CFRP (S5) and section enlargement (S6) exhibited 77.4% and 130% higher ultimate load capacities, respectively, in comparison with the control slab. The increase in the ultimate strength for slab specimen S5 is in agreement with the results reported by Toong and Li [22] even though the ratio of CFRP strip area to the overall cross-section area used in this study is minimal (0.04). Moreover, ferrocement cover repaired slab (S4) exhibited no increase in the ultimate capacity of the specimen compared to the control slab, which mirrors the conclusion reported by Al-Kubaisy and Zamin [17].

3.2.1. Slab deflections

Figure 19 shows load–deflection for each of the slabs. These deflections recorded at the mid-span. The slab specimens exhibit almost similar stiffness except for S6 (repaired by enlargement), where the deflection has decreased due to the added stiffness of the extra concrete layer. However, after two-third of the ultimate load, these specimens show diverse levels of ductility patterns. S3 (epoxy injection) and S4 (ferrocement layer) exhibited 15% lower values of maximum deflections compared to the control slab, while repairing the crack with grout pouring showed 20% increase in maximum deflection compared to the original slab.

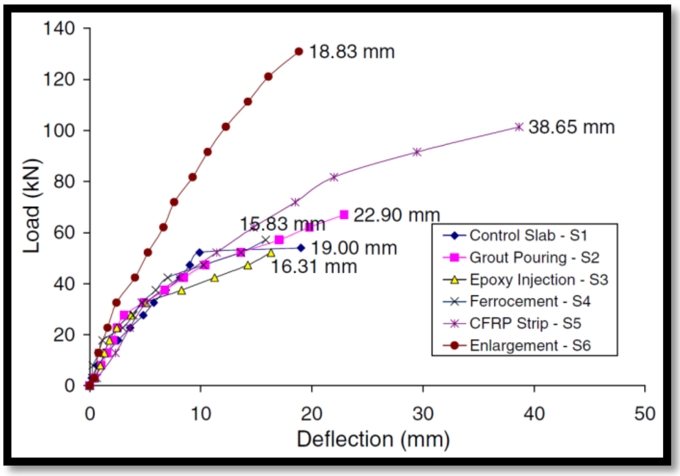

Figure 19. Load–deflection curves for all slabs [4]

3.2.2. Strain distribution

Figure 20 shows the variation of the concrete compressive strain at the mid-span and 25 mm below the top fiber of the reinforced concrete slab specimens versus the applied load. It recorded during the test that the Neutral Axis was shifting upwards with the increase in the applied load, and during different loading phases, its depth changed from 40mm to approximately 30 mm in S1, S2, S3, and S4. For specimens strengthened with CFRP and reinforced concrete layer (S5 and S6), the depth of the neutral axis changed from 70mm to approximately 45 mm near failure load. Figure 21 represents the concrete strain in different slab specimens when the applied load is equal to 50 K.N. (nearby failure load of the control slab).

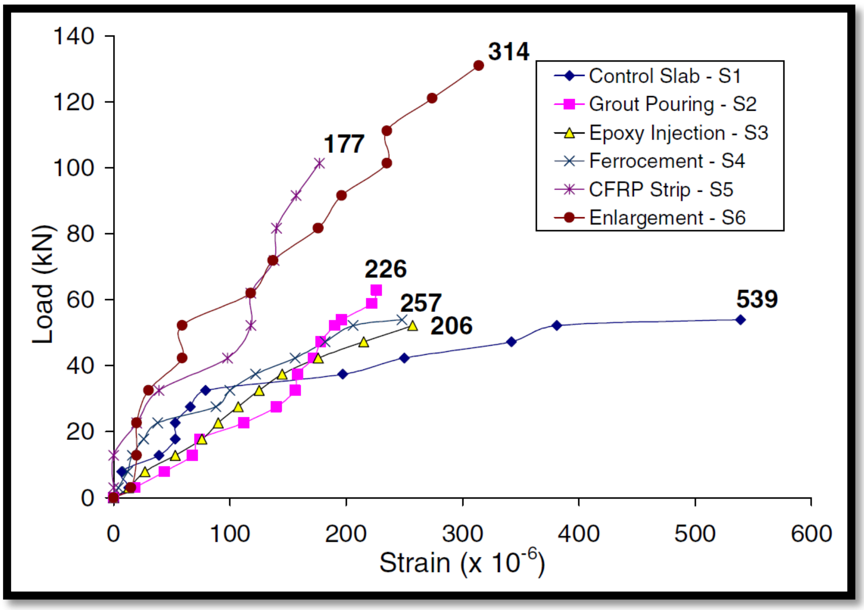

Figure 4. Variation of concrete compressive strain for all slabs [4]

All the slab specimens exhibit lower strain values compared to the control slab. In specimens S2, S3, and S4, a decrease ranging between 30% and 50% found while in S5, the compressive strain reduction observed to be 65%, and in S6, it perceived to be 85%. For the specimen reinforced with an additional R.C. layer, it found that the strain in the extra reinforced concrete layer is not compatible with strain in the original slab. However, initially, both layers act as a composite section. It is due to providing an insufficient number of shear connectors, which leads to the occurrence of horizontal longitudinal cracks between the two layers.

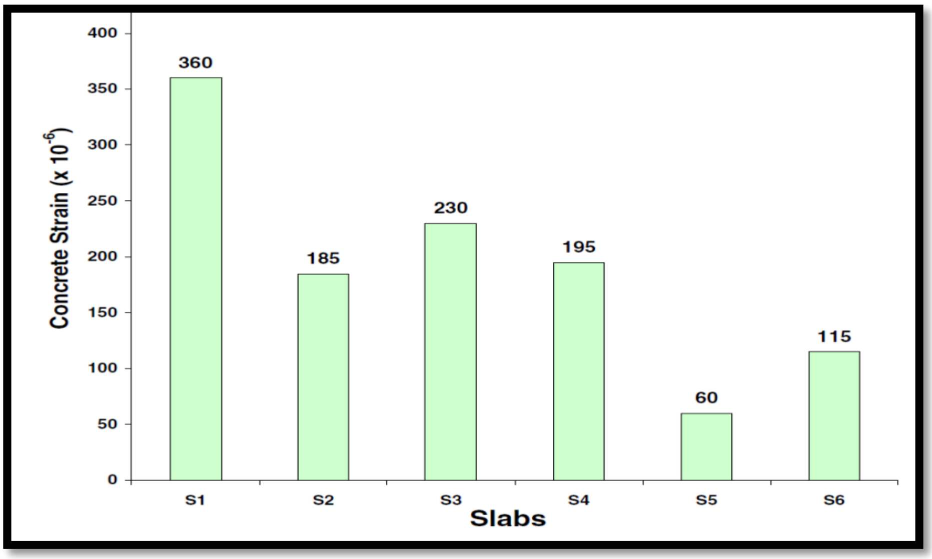

Figure 5.Concrete compressive strain at 50 K.N. load level [4]

IV. CONCLUSIONS

The first step of repairing cracks in concrete slabs is finding and considering the cause of initiation of the cracks, and based upon it, the type of repair which best resists the cause of crack initiation should choose. Otherwise, any attempt to repair the cracks will be temporary, and it will reoccur. The desired outcome of the repairs also determines the criteria of selection of crack repair procedures. Five methods of crack repair we presented discussed and explained, including the techniques, advantages and disadvantages, and areas of application of each. After reviewing controlled comparisons, the following conclusions could be drawn:

1. If the repair process conducted accurately for the repaired slabs using all five methods of slab repair can have similar or higher cracking loads and ultimate loads compared to the original slab.
2. Grouting method, epoxy injection method, and ferrocement applying method showed identical behaviors to that of the control slab in terms of ductility and strength performance. In other words, these techniques of crack repair can adapt to the ordinary reinforced concrete design standards for concrete slabs.
3. Section enlargement and Carbon Fiber Reinforced Polymer methods exhibited superiority in structural performance in terms of strength. However, these slabs observed to be less ductile than the control slabs.
4. All techniques of crack repairs mentioned in the current study can restore the structural performance of the slabs at the very least and consider as safety measures for crack repair in concrete slabs.

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