# FRP STRENGTHENING OF RC BEAMS WITH CORRODED REINFORCEMENT

Master’s thesis in Structural Engineering and building technology

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# Abstract

The thesis mainly focuses on the strengthening of the corroded reinforced concrete structure by studying the background of corrosion from its grassroots level. As we know, the corrosion of steel reinforcement is one of the most common problems existing in RC structures during the service life. Fiber-reinforced polymer (FRP) is a type of composite material characterized by superior strength, light-weight, and high resistance to corrosion. The corrosion damage has significant effects on the strength and deformability of the reinforcement. It also introduces longitudinal cracks in the surrounding concrete due to the volume expansion of the corroded reinforcement. Therefore, the strengthening activity without considering the critical corrosion damage in the RC structures might not achieve the improvements as expected.

Usage of FRP composite material to retrofit to strengthen the RC structure has been a vastly studied issue for the past few decades. Nevertheless, most of the research so far is limited to the FRP strengthening of RC members without considering the effects of corrosion damage on the design and application of the strengthening scheme. This study gives an elaborative concept of the effect of corroded reinforcement on the structural behavior of degraded RC beams concerning serviceability, load-carrying capacity, and structural safety, summarize and review the traditional strengthening solutions for corroded RC members mainly concerned with the ultimate load-carrying capacity and ductility of the corroded beam. Detailed literature review of the strengthening solutions of corroded RC beams using FRP composites by comparing various aspects of strengthening like the levels of corrosion, the requirement of patch repair work before strengthening, and how various FRP composites exhibit their maximum strengthening by studying the failure modes of the beam loaded until failure. With an outcome of deep understanding of the behavior of corroded RC structures and knowledge from the review of previous works of the state of art in strengthening methods using FRP composites. This review work could be used as a key for future researchers to carry out their experimental tests using FRP

Keywords: FRP, corrosion, strengthening, RC beam, Flexure, ductility.

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# Preface

The thesis work has been carried out from January 2020 to June 2020. The work is a part of a research work review concerningthe strengthening of FRP corroded RC beams using FRP composites. The project is carried out at the Department of Structural Engineering, Concrete Structures, Chalmers University of Technology, Sweden.

This part of the project has been carried out with Reza Haghanias anexaminer and Jincheng Yangas a supervisor, Department of Structural Engineering at the Chalmers University of Technology.

Göteborg June 2020

# 1

# INTRODUCTION

## 1.1 Background

In recent years, the demand for expanding the service life and increasing traffic load on the existing structures highlighted concern on the durability and capacity of the existing infrastructure. The main durability issue which leads to deterioration of reinforced concrete structures is the corrosion of steel reinforcement [1]. The paramount of all is the one due to steel corrosion. The damage due to corrosion or cracks due to combined mechanical and chemical factors implies the need for an appropriate methodology of structural rehabilitation [2]. The existing structures have to be maintained to carry the future load since the structure cannot be replaced. degradation of structural elements takes place when exposed to aggressive natural climatic conditions and exposure. Eg. offshore structures, basement parking garage, bridges, and flyovers. Due to this degradation of components affects the service life and ultimate capacity of the structure. Damage and residual capacity assessment as well as suitable repair and strengthening of deficient reinforced concrete members are urgent for most existing structures.[3]. Therefore understanding the behavior of the structural elements the duty of the responsible authorities such as concerned engineers, stakeholders, and researchers to carry out studies to overcome this issue. FRP processes high tensile strength. This provides excellent material to take the tensile force to strengthen RC structures in flexure. With the current improvement in the quality of adhesives for construction, the bonding between FRP and concrete is generally satisfactory.[4]

Bencardino F, Carloni C, Condello A, et al., in 2018 had done a review work on several papers by considering the drawbacks of epoxy resins, a study on inorganic matrix-like cement mortar and noticed an increase in load-carrying capacity of the strengthened beams compared with control beams which are considered to depend on the thickness of the fabric used like carbon-FRCM, PBO- FRCM and steel -FRCM. The authors also tried to predict the formula for debonding strain for different materials like carbon, steel, etc. [5] Belal Almassri, Firas AL. Mahmoud and Raoul Francois conducted experimental and finite element study on corroded RC structures using NSM-CFRP rods. From this review, near-surface mounted (NSM) technique for strengthening corroded RC structures considered as the most common technique. Three beams that were kept for natural corrosion for about 25 years were repaired by grooving CFRP rods at the tensile face of the beam. The results were compared with the 2 un-corroded beams. The beams were tested in a three-point loading system until failure mode occurred to find the ultimate capacity of the beams which was compared with the FE modeling. The experimental results showed an increase in flexural capacity with the expected failure mode of cover separation. Kreit et al. and Al-Mahmoud conclude that the use of the NSM-CFRP technique in the strengthening corroded RC beams improves the overall structural behavior by increasing flexural capacity and also a considerable increase in ductility by avoiding early failure due to pit-corrosion compared to un-strengthened beams. Also, they confirm this technique has fewer disadvantages compared to the EBR technique. [6]. The following table below defines why FRP as a material is a better strengthening solution than steel or concrete based on their respective properties.

| **Properties** | **FRP** | **Steel** | **Concrete** |
|---|---|---|---|
| **Unit weight** | 10 Kg/m$^2$ | 7800 Kg/m$^3$ | 2400 Kg/m$^2$ |
| **Thickness(mm)** | 0.11-0.8 | 150 | - |
| **Elastic modulus(GPa)** | 50-200 | 200 | 45 |
| **Tensile strength(MPa)** | 1000-4000 | 400 | 2-5 |
| **Ultimate strength(MPa)** | 1000-4000 | 420 | 35 |

Table 1 Properties of FRP, steel, and concrete

*Information gathered from : (PDF) Strengthening of reinforced concrete beams by using fiber-reinforced polymer composites: A review. (n.d.). Retrieved from https://www.researchgate.net/publication/332977993_Strengthening_of_reinforced_concrete_beams_by_using_fiber-reinforced_polymer_composites_A_review*

Corrosion in steel which affects the serviceability of structure is improved by repair work using the EBR-CFRP technique. Here 14 beams were grouped and tested. Out of which 3 beams were not corroded and strengthened by CFRP laminates and remaining 11 beams were corroded using accelerated corrosion technique done at different levels up to 31% steel mass loss with 6 beams retrofitted using CFRP laminates and the rest were tested without repair work added. The surface was sandblasted and washed before the application of the EBR technique to remove the damaged surface and to make a good uniform surface for the bondage between FRP and concrete. CFRP laminates were provided both in longitudinal and in transverse directions of varying numbers of layers. Retrofitting technique was carried out in 2 ways by wrapping CFRP laminates continuously throughout the middle span along with U-strips at the edges. Few beams were also wrapped strips with intermittent spacing between them. All the beams were tested under a 4 point loading system. The experimental results conclude that the beams wrapped continuously along the middle span with both longitudinal and transverse U-wraps exhibited in the highest strength under all levels of corrosion which was compared with the corroded and unrepaired beams. Laminating the structural concrete element with FRP wrapping provides an external pressure that resists internal displacements caused by the volumetric expansion of corrosion products and hence reduces corrosion and bond splitting cracks.[7] Hanseung et al. [8] mentioned that the beam strengthened using CFS (carbon fiber sheets) bonding, reduced the stresses and the ultimate capacity of the beam was increased.

Samanta A et al. [9] carried out a review work on FRP composites for corroded RC structures and concluded FRP had been widely accepted in the industries in which type of material like glass is preferred more due to being less expensive compared to CFRP. The review includes common failure modes of strengthening RC beams like concrete crushing, cover separation, debonding, and laminates separation. Almusallam et al. [10] in 2013 investigated the flexural strength using NSM-CFRP rods and concluded that an increase in flexural capacity and stiffness with an increase in GFRP reinforcement with CFRP rupture and concrete crushing as the mode of failure. Khaled Soudki et al. [11, 13] confirmed that the effectiveness of using CFRP increased the ultimate capacity of the beams which was almost twice compared to un-strengthened beams. Also, the CFRP material resulted in allowing less chloride diffusion by protecting the steel reinforcement from getting corroded at the early stages. This enhanced the durability of the structure by acting as the protective layer for the structure when they are exposed to severe environmental conditions. Mechanical behavior of corroded RC beams retrofitted using NSM-CFRP rods was experimentally studied by Almassri B, Kreit et al. [14-15] resulted that NSM-CFRP rods could increase the ultimate load capacity making the structure more ductile. Also as expected the mode of failure due to this technique was concrete cover separation which was noticed in both corroded and control beams. Finally, they mentioned this technique can be applied for strengthening both corroded and the control beams to enhance the structural characteristics of the beam. Achudhan, Deepavarsa, Vandhana, Shalini (2019) corroded beam electrically and strengthened using EBR-GFRP laminates and calculated the ultimate load capacity until glass fiber reinforced polymer was ruptured where they noticed an increase in strength and stiffness with a significant increase in ductility. [17] With the steel mass loss up to 50%, Ahmed Abdel and Hui shen conducted an experimental test for corroded RC beams using CFRP U-wraps. They concluded that with 50% steel mass loss without repair work nearly lost 57% of load-carrying capacity and with patch repair technique 42% of load-carrying capacity was recovered. [18] Saidy, Goitseone malumbela et al in 2011 tested the effectiveness of patch repair technique before strengthening the corroded RC beams using CFRP laminates and concluded that patch repair work prevented further corrosion and also they noticed an increase in capacity and stiffness. [20-21]. Khaled et al in 2000 experimented with the beams corroded at different levels from 5-15%, strengthened with CFRP laminates using epoxy resins. The beams were tested under 4-point loading until CFRP rupture and they noticed ductility loss but stiffness and ultimate strength were improved compared to the un-strengthened beam. El Maaddawy, T., Soudki, K., and Topper, T. (2005) developed a computer-based model to determine the load-deflection relationships for the corroded strengthened beams and compared the results with the lab experiments conducted. They confirmed that the model Computer program- ACFRP (Analysis of corroded and FRP repaired beams) gave accurate results. [32] Saidy, Jabri, Halim, and shidi in 2011performed experimental tests by wrapping CFRP sheets for corroded structures under different designed schemes like scheme 1-longitudinal face along the length of the tensile side, scheme2- longitudinal sheet along with U straps at the tension side and under scheme 3-CFRP wrapped around both sides of the beam (U-wrap). They concluded that the U wrap technique resulted in a more effective restoration of strength. [33].Su Linwang, Cai Jian, Chen Qingjun, Li Guobao, and Zhao Juan in 2015 investigated the flexural behavior of corroded RC beams that were subjected to different corrosion levels upto 69.84% and repaired with CFRP laminates. The authors also compared the results with patch repaired work and concluded that CFRP does not exhibit its strength at a high level of corrosion with beam failure due to lower bond stress.The effectiveness of strengthening by CFRP after surface preparation was higher than bonding directly, flexural capacity was increased up to 30% to 50% than un-strengthened with restrained crack width and increased stiffness.[36]

Balamuralikrishnan R and Thirugnanasambandam S in 2016 rehabilitated the corroded RC beams using two different materials carbon and glass. They studied the results from both GFRP(3mm thickness) and CFRP laminates bonded externally. The corroded beams upto 50% level of corrosion were patch repaired with sandblasting technique. They noticed the bond failure with a reduction in deflection. They also concluded that load carrying capacity for beams strengthened with high corrosion level cannot be effective in exhibiting its strength. Also, CFRP strengthened beams showed poor ductility. [39] Leema A et al.in 2014 [40] tested the behavior of corroded beams upto 10-25% steel mass loss, strengthened using UDC-GFRP (uni-directional clothing) laminates of 3-4mm thickness with patch repair work. They showed UDC-GFRP strengthened beams increased ultimate strength upto 86% for 10% steel mass loss and nearly 79% increase in strength for the beams strengthened with 25% steel mass loss. They also concluded that UDCGFRP strengthened beams enhanced the ductility. [40] Triantafyllou in

2018 studied the effect of patch repair work in strengthening the corroded beams using both the techniques EBR and NSM. The author subjected the beams at three different corrosion levels and used carbon laminates. He concluded that at a low level of corrosion, NSM-CFRP strengthened beams could take a higher load compared to the EBR technique. At a medium level of corrosion, the author noticed the EBR technique was effective. At high levels of corrosion, the author specified patch repair work is essential and showed beams strengthened with the EBR technique could take twice the load when compared to the capacity of beams strengthened with the NSM-CFRP technique. [42] Also in 2019 he conducted an experimental study for the effectiveness of patch repair work for corroded RC beams strengthened with the NSM-CFRP technique. He concluded patch repair work had restored the load capacity and also explained pitting corrosion and local corrosion in the reinforcement are the main causes for tensile deformability.[43]

## 1.2 Aim and objective of work

The thesis mainly focuses on the strengthening of the corroded reinforced concrete structure. by studying the background of corrosion from its grassroots level. As we know, the corrosion of steel reinforcement is one of the most common problems existing in RC structures during the service life. The corrosion damage has significant effects on the strength and deformability of the reinforcement. Usage of FRP composite material to retrofit to strengthen the RC structure has been a vastly studied issue for the past few decades. This study gives an elaborative concept of a review of the strengthening of RC structures with corroded steel reinforcement. Within this overall study of aim, some objectives are related to different stages of this project.

- Why understanding the effects of corroded steel reinforcement on the structural behaviorof degraded RC beams are studied before strengthening.
- What is the purpose of reviewing and evaluating the traditional strengthening solutions for corroded RC members? mainly concerned with the ultimate load-carrying capacity and ductility of the member.
- Reviewing how research publications approached the flexural strengthening of corroded RC structures/beams on utilizing different FRP composite materials.
- Epitomize and identify which methods are effective to repair and strengthening methods using FRP composites to improve the structural load-bearing capacity and restore the ductility of corroded RC beams.

## 1.3 Significance of work

The original contribution and deliveries of this thesis work are as follows:

- The intension behind the study to find answers for how evaluation of an existing corroded structure, causes of deficiency, field application, and factors affecting the selection of strengthening solutions.
- The type of strengthening methods and its effectiveness using FRP composites can be adopted of various corrosion-related problems such as type of exposure conditions and level of steel loss in the section.
- The study mainly focuses on flexural capacity and restoration of ductility which is one of the main aspects of the present state of infrastructure.
- Various levels of analysis and experiments carried out by research publications and their evaluation presented to know the expected failure mode which can be seen after the application of maximum load.

The importance of this work has major significance in the present growing world, almost all the structures in the world need to be maintained one or another way. The research gives knowledge about the statistics of structures that are to be rehabilitated and maintained in terms of capacity and strengthening in the structure for the increasing traffic in the cities around the globe. It seems that the strengthening of the RC structure is a global problem. so, therefore, it becomes the main contribution to the responsible authorities who are responsible for strengthening the existing structure. Reviewing this problem FRP comes into play to maintain, strengthening the structure due to its finest mechanical properties makes the structure gain high capacity and durability, of course, needs proper installation. The review work delivered in the thesis is meaningful to the industry by providing the state-of-the-art FRP solutions studied in the latest research to strengthen the corroded RC structures. Based on the review work, the effective FRP strengthening methods revealed or proposed for the corroded RC members can also be applied to the experimental test of the ongoing projects in the company.

# 2

# EFFECT OF CORROSION

## 2.1 Structural complication due to corrosion

The structural problems arising after corrosion are wide range, which contributes to bad structural behavior of RC structures in its service life. Such as fatigue problems, reduction in strength, limited ductility, week bond strength, loss of shear capacity. As a consequence of corrosion, it reduces the effective cross-section of structural components. This will reduce the axial, and flexural strength of elements, and makes them structurally weak. Even if corroded elements look stable, it does not mean they are safe; in fact, the corroded structures become vulnerable for ultimate loads. Corrosion of steel bars produces rust materials that occupy a larger volume than the original steel. Due to this large volume of rust creates pitting stress acting on the concrete leading to cracks with larger width making spalling of concrete cover. Meanwhile, these cracks will intensify the corrosion process thereby changing the structural behavior of the structure i.e. the interaction between the steel reinforcement and surrounding concrete. Another complication, structural effect of corrosion is on the fatigue strength of steel elements, connections, and RC elements. Corrosion may accelerate fatigue crack propagation in structural steels. The development of pitting corrosion introduces additional points of stress concentration at which cracking may develop, which will reduce the fatigue strength of the structure. Corrosion can significantly reduce the ductility of RC sections. This is critical in seismic design and evaluation. Corroded sections have lower ductility, which means their plastic deformation is limited. This will affect the seismic response of the elements. Corrosion of reinforcement in the lap splices will affect the load transfer in the laps, preventing the to develop yield stress. Effects of corrosion due to chlorides and its structural effects are discussed following Fig [1]

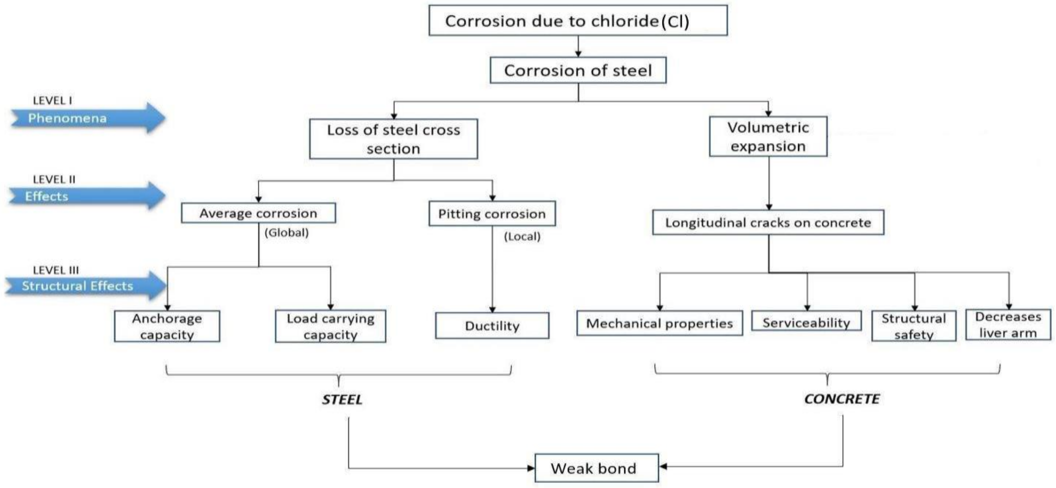


Fig: 1 Effect of corrosion on a structural level

## 2.2 Volumetric expansion

Corrosion of concrete causes volumetric expansion in steel rebars, normally the expansive pressure exerted due to the volumetric change in the steel rebar in the concrete, this induces tensile strains in the concrete, and it is proportional to the degree of corrosion. When the expansion action begins repeatedly, tensile strains are developed and induce cracks in the enclosing concrete and also at the surface of concrete cover, Hamidun Mohd Noh [51]. To examine the cracking of concrete due to steel corrosion. It is important to know the link between internal pressure developed from corrosion and the amount of corrosion of steel bars.

The type of oxide layer and its properties as a corrosion residue influences on the corrosion cracks in the concrete. The most prominent factor is the expansion ratio of the oxide which mainly depends on the type of oxide layer formed. Providing on the level of oxidation increase in the volume of rebar is commonly around 2 and maybe increased up to 5 times than the original volume which gets consumed during the corrosion process due to the formation of various corrosion residue. Nevertheless, Yoshimi Sonoda [51] claimed that the effective expansion ratio may be less than that corresponding to a given type if the oxide diffusing in the porous structure of the concrete. When the corrosion of reinforcement evolves significantly, the residual corrosive products enlarge continuously thereby generating internal pressure to the surface of concrete around the steel rebar. The rapid corrosion of reinforcement not only affects the serviceability of concrete or even spilling of concrete cover, but it also affects the structural safety thereby decreasing the load-carrying capacity of the RC structure. Besides, the physical effects of corrosion include loss of steel area, loss of bond strength between steel reinforcing bars and concrete, and reduce concrete strength due to cracking service life of the corroded structure is often identified as the time for concrete cover cracking, Pilate Moyo[52]. The volumetric expansion of the steel rebars in the RC structure generates extremely high tensile forces within the concrete. On the other hand, it’s known that the tensile strength of concrete is relatively lower than the compressive strength of concrete it is susceptible to the formation of cracks from the rebar to the surface which is inclined cracking or between the rebars delamination which leads to a weak bond between concrete and steel. Due to the formation of these cracks, this promotes enter of oxygen and any kind of salt-based moistures entering directly to the rebars at a faster rate which hikes the corrosion rate. This eventually leads to the spelling of the concrete from the surface, it is said that the deep of corrosion damage at initial stages, is believed to be 200mm Roberto Capozucca et al.[53].

It is well-researched in Fg. [2] that the corrosion residuals occupies a greater volume than the parent steel due to which tensile stress are developed causing cracking od concrete cover, steel corrosion reduces the structural integrity of the concrete by loss in the area of steel, cracking of concrete cover and loss in the bond between the surrounded concrete and steel As a result of expansion in the steel rebars in a corroded RC structure there is a substantial decrease in the liver arm and mechanical properties of steel such as strength, ductility, hardness, impact resistance, flexibility, and fracture toughness. The below figure briefs abut the volumetric expansion of corrosion products.

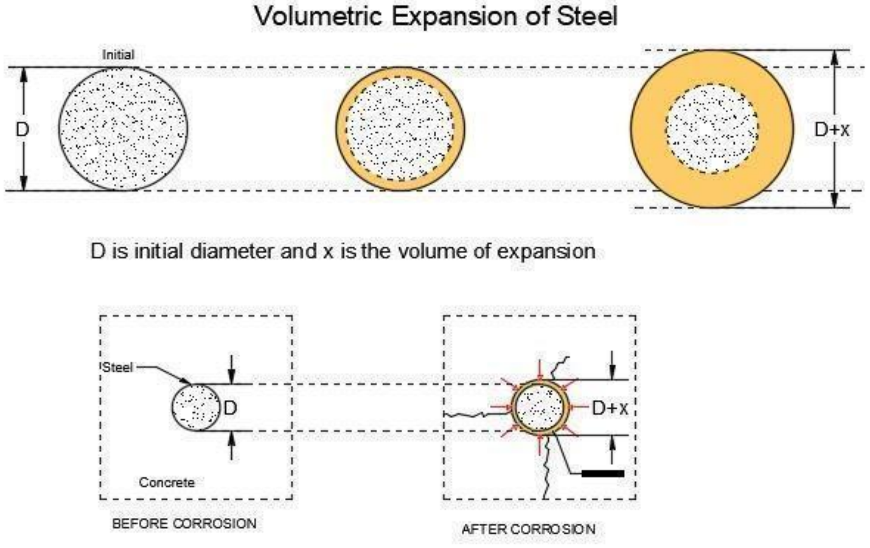


Fig: 2 Volumetric expansion of steel

## 2.3 Loss of cross-section of steel

The effect of corrosion on RC structure results in loss of cross-section of steel rebar from its actual cross-section depending on what type of corrosion level it is undergoing based on the age of RC structure and type of exposure condition. This will be more clear when we know about pitting corrosion which is Chloride is particularly damaging to the passive oxide which initiates pitting corrosion in the concrete. Pitting corrosion of rebar occurs for RC structures exposed to a chloride environment. The highly traced form of corrosion of steel rebar can cause a significant reduction in cross-section of the rebar up to 80% loss of cross-section was observed for a 40-year-old bridge in the Canadian bridge which was demolished in 1999, Stewart[55]. Pitting corrosion is non-homogenous along rebars, on the other hand, it is highly spatially due to spatial variability of concrete and steel material properties. The effects on steel rebar due to corrosion modifies the external surface of the steel due to pitting the steel section of the corroded steel rebar is no longer circular and it varies considerably along its boundary and its length, Hence, the residual diameter is better defined by loss of weight, Mohammed Morsy [57].

The weakening of the bond is caused by the development of a less firmly adhering interstitial layer of corrosion products between the concrete and the rebars, and reduction in the bar ribs due to pitting, Roberto Capozucca[53]. Pitting corrosion is localized corrosion which occurs locally in the RC structure i.e. at the ends of the beam or the mid-span of the beam. Average corrosion is a type of global corrosion that occurs on the whole structure which is very dangerous since the corrosion has reached its maximum where the beam or structure won’t have enough strength from its reinforcing rebar. Pitting corrosion leads to a significant loss of cross-section of rebar and accordingly reduces the strength of the reinforcing bar. This reduction in strength of the reinforcing rebar also depends on the presence of pitting with various depths and shapes. This leads to thinking regarding the mode of failure of corroded reinforcing steel and the possibility of stress concentration associated with pit geometry, M. S. Darmawan[54]. There is general agreement that the mechanical behavior of reinforcing rebars changes from ductile to brittle as corrosion loss in steel cross-section increases. This is less evident with the level of corrosion loss during this transmission from ductile to brittle behavior how this is affected by the steel type, M.G. Stewart [56]. In the case of pitting, the ultimate strain is severely reduced by corrosion. It is sufficient with only 10 % of non-uniform corrosion to reduce the ductility of bars embedded in the concrete to below the minimum requirement specified in design codes for use in high ductility. Furthermore, Almusallam[58] concluded that the stress-strain characteristics of corroded reinforcements indicate a decrease in the ductility with an increase in the corrosion level. Other steel parameters, such as yielding and ultimate stresses, are significantly reduced by corrosion. Various effects may occur due to the formation of the pits on a reinforcement bar subjected to tension, local bending on the pitted cross-section due to a displacement of the center of gravity, as well as stress localization on the tip of the pit, may explain the important drop in the main mechanical properties of the steel bar, Fernandez [39]. The formation of large and localized strains due to such phenomena is also an important consequence; since the length of corrosion pit is short, the average strain in the entire bar becomes lower than the strain at a local pit Stewart [55], causing the corroded bars to fail at deformations much smaller than that of the original bar; thus, corrosion causes the reinforcement to behave in a brittle manner, Coronelli[14].

## 2.4 Structural behavior of corroded RC structure

The various structural behaviors of RC structure in its service life such as stiffness, load carrying capacity, and force redistribution is affected by the corrosion of reinforcement. Due to various factors and there effects the functionality of the RC structure changes completely such as loss of cross-section area of steel rebar leads to a reduction of shear and moment capacity of the structure which in turn refers to low stiffness in the structure. The shift of bar ductility to non-ductile material influences moment and force redistribution and resists the load-carrying capacity of statically indeterminate structure this may also lead to failure of the structure under severe seismic load. Due to volumetric expansion, there will be spilling of concrete which leads to cover cracks as discussed before. The cracked parts reduce the concrete cross-section and cover. The compressive part of the concrete reduces the internal liver arm, as a result, it decreases the bending capacity of the structure. On the other hand, due to these cracks in concrete, there will be confinement interaction between the rebars and concrete which affects the shear capacity and anchorage capacity of the structure. If there are larger cracks in this section due to corrosion the structure has reached its maximum tensile capacity and tension load tends the structure to failure causing tensile stress in the structure which causes large cracks widths and wider cracks, Mohammad Tahershamsi[16] The generated cracks also affect the load-carrying capacity of the structure in its service life without any coverage to the reinforcement thereby rebars are exposed to external environment and moisture which speedup the corrosion thereby changing the force distribution in the structure.

The structural behavior of corroded RC structures, structural effects of corrosion can be determined as a change in geometry and properties i.e, reduction in cross-section area of the steel rebar due to corrosion the rebar is no more circular and ductility, removal of spalled concrete cover and surface, modification of concrete response due to corrosion cracks, and modification of bond-slip properties, Karin Lundgren[24]. Steel corrosion in reinforced concrete leads to crack along the reinforcement which is known as secondary cracks, resulting in a reduction in bond strength and a reduction in cross-section of steel. Concerning the ultimate behavior, the loss of steel cross-section is the main parameter which leads to a reduction of bearing capacity and ductility. G. Arliguie part 1[59]. Corroded reinforced concrete members the concrete cracks caused by the corrosion of compressive rebars have no significant influence on the structural behavior of RC beams in service life. The corroded RC structure has a loss of bending stiffness, dissymmetrical behavior could only be attributed to the reduction in steel cross-section and the loss of bond strength. G. Arliguie part 2[60]

# 3

# EXISTING SOLUTIONS FOR STRENGTHENING OF CORRODED RC MEMBER

## 3.1 Synopsize of strengthening solutions

FRP( Fibre-reinforced polymer) is a thin fiber material which is made up of different materials and configurations. FRP is widely used in the retrofitting and strengthening techniques which helps to restore strength, ductility, etc., These materials can be used in the form of laminates/sheets, rods or strips by using suitable adhesive material for bondage between concrete and FRP.  Strengthening of corroded RC beams to improve the structural behavior led to the invention of new approaches. Several techniques are frequently tested in strengthening corroded RC beams using FRP composite materials. Deterioration of RC members due to chloride corrosion had been strengthened using various techniques. Such emerging techniques involve using FRP, Steel, and FRC, these methods are not only used for strengthening corroded RC structures but also to increase the performance of the structure. The use of steel for the repair and strengthening is the oldest technique which emerged into using fiber reinforced concrete. Comparing each methodology with their functional properties and drawbacks, using FRP in the industry has been increasing with different techniques and materials. By testing and improvising each technique using FRP had been more advantageous, effective, and easy to work with. The special properties of fiber-reinforced material involve non-corrosion, high tensile strength, lightweight, and are more durable compared to steel bars. FRP properties vary based on the material used like carbon, glass, aramid, basalt, etc.

### 3.1.1 External bonded reinforcement(EBR)

This technique involves strengthening of corroded RC beams by providing different configurations to the external surfaces. Such configurations can be provided in layers The deficiency of longitudinal reinforcement in beams and columns due to corrosion, leading to flexural failure.  In such cases, the bending capacity of concrete elements can be increased through the use of externally bonded FRP plates and, strips at the tension side of the beam. Providing the bond between the FRP laminates and concrete prevents the spalling of concrete cover and longitudinal steel rebar is controlled. Flexural and shear capacity of the corroded beam can be improved by externally bonded reinforcement by proving FRP laminates in the transverse direction to the RC member [28]. This system can be provided in the form of laminates or wraps in several layers with different materials. Efficiency and flexural behavior of strengthened RC beams were studied [6] using EBR-CFRP plates to conclude that the beam flexural capacity was increased which later failed due to debonding. Also, the beams were tested by an increasing number of layers of EB-CFRP[10]. In the paper[17] researchers experimented by using EBR-CFRP laminates along with U wrapping resulted in less deflection with improved load capacity and fewer shear cracks.

Fig:3 Application of FRP  External bonded reinforcement

*Picture gathered from (n.d.). Retrieved from https://www.concreteconstruction.net/how-to/repair/externally-bonded-reinforcement-for-strengthening-concrete-and-masonry-structures_o*

### 3.1.2 Near surface-mounted (NSM)

This technique uses bars/strips strengthened internally with FRP composites ina pre-saw groove at the tension side of the beam that can be grooved along the tension side of the beam as shown in Fig. 4,it is an effective method to increase the load-carrying capacityat a negative moment region of strength deficient beam and slabs [28].Flexural capacity was increased by using  NSM CFRP strips in repair and strengthening of corroded RC beams under service loading by researchers Garyfalia Triantafyllou, Theodoros Rousakis, and Athanasios Karabinis [1]. NSM-GFRP bars grooved with more than one layer resulted in higher flexural capacity and less damage due to debonding failure which was tested by Almusallam, T. H, and Elsanadedy[4 ]. The structural behavior of RC beams strengthened with a different number, type, and varying diameter of GFRP bars were tested[8] which increased flexural capacity and stiffness with an increase in reinforcement ratio provided.

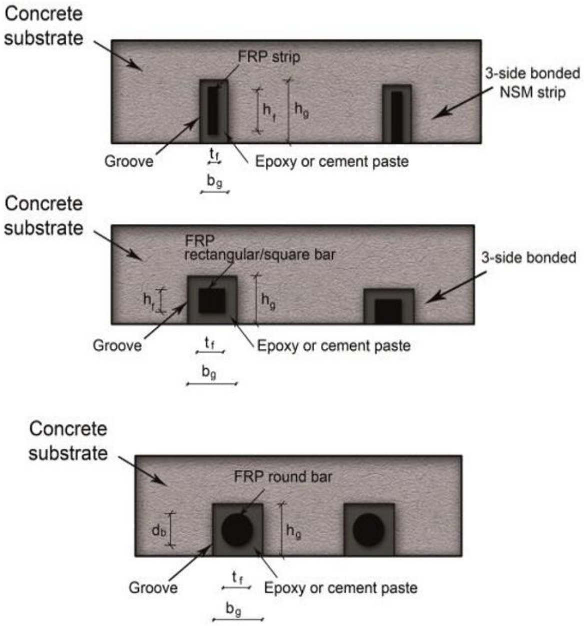


Fig:4 Near-surface mounting with FRP composite rod

*Picture gathered from Khalid Heiza, Ahmed Nabil, Nageh Meleka, and Magdy Tayel (2014).  State-of-the Art Review: Strengthening of Reinforced Concrete Structures – Different Strengthening Techniques.Civil Engineering Department, Faculty of Engineering, Menofia University, Egypt*

### 3.1.3 Wrapping

This another technique to increase the shear capacity, flexural strength,and service life of the deficient RC member[28] but this method is followed for strengthening corroded RC members. It is the process of externally wrapping the FRP composites over the corroded beam there are various types of the application shown in Fig.[5],fully wrapping, U wrapping (U jacketing), and side wrapping. U – wrap is most preferred due to its anchorage along the side of the beam by protecting the concrete cover.To overcome the early failure due to debonding and shear cracks, a strengthening technique called U-jacketing had been used by researchers. This is considered to be an external strengthening method. This method can be applied by using externally bonded fiber-reinforced polymer (EB-FRP) wrapped around the perimeter of the rectangular section which was experimentally carried out by Constantin E. Chalioris Adamantis G. Zapris and Chris G. Karayannis. Carbon-FRP sheets were wrapped along the 3 sides of the beam and the entire length and the test results indicated shear capacity was significantly increased with the failure mode due to the brittle nature of the material.

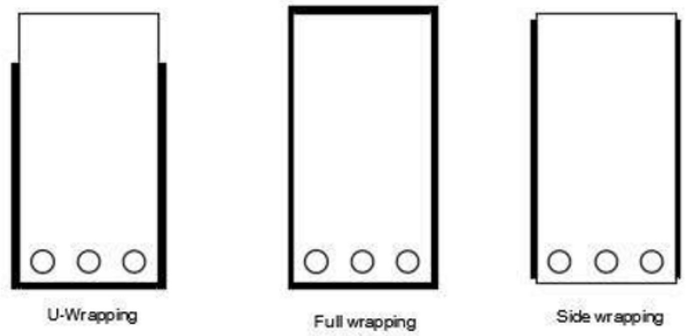


Fig:5 Flexural and shear strengthing scheme using FRP composite wrapping

### 3.1.4 Prestressed Composites Systems

This conventional retrofitting technique to strengthing structurally deficient RC member by post prestressing FRP composite before bonding with advanced clamping procedure at the end anchorage and release after the adhesive is hardened as shown in Fig. 6. As a result of prestressing the pre-existing cracks are closed thereby improving durability and service life. It culminated that strengthing method using prestressed FRP is well researched yet in strengthening the industry[28].

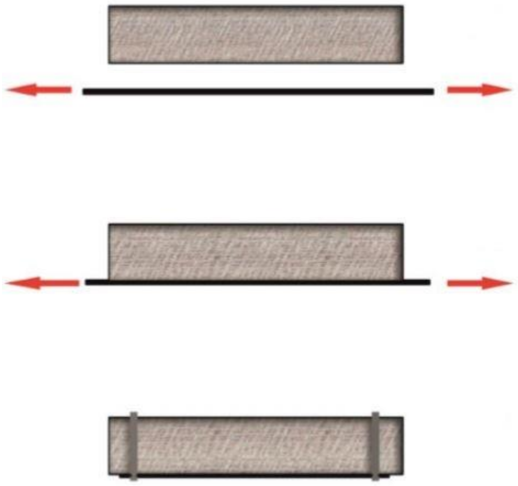


Fig:6 Strengthing with Prestressed FRP composite strips

*Picture gathered from Khalid Heiza, Ahmed Nabil, Nageh Meleka, and Magdy Tayel (2014). State-of-the Art Review: Strengthening of Reinforced Concrete Structures – Different Strengthening Techniques.Civil Engineering Department, Faculty of Engineering, Menofia University, Egypt*

## 3.2 Strengthening of RC members with Steel and Fiber-reinforced Concrete

Steel had been used in rehabilitation of concrete structures over several years. SRP (Steel reinforced polymer) in the form of twisted steel bars/rods has higher strength compared to the reinforcement bars which are usually used. Using steel in the repair and strengthening works is one of the old techniques on which several researchers investigate to overcome the drawbacks. The important characteristic of using steel results in good ductile behavior of the structure. Steel can be used when the structure needs to be resistant to fire. Also to overcome the drawback of debonding which commonly occurs by using FRP, wherein steel slows down the debonding failure due to its ductility property. This behavior was experimentally tested by Paolo Casadei and Antonio Nanni [mention year] in which 3 beams were strengthened by providing one beam with a single layer of SRP and another concrete beam with 2 layers of SRP anchored using SRP-U wraps. An increase in flexural capacity was found to be more effective from a beam with 2 layers of SRP. and also resulted in a delay of debonding of SRP laminate.

Concrete is one of the common materials used in the construction field. However, it can be used in patchworks and other minor works due to its good bondage capacity. Less research work can be found in the strengthening of corroded RC beams by using concrete. Some of the researchers have been carried out in the past few years to strengthen deficient beams using HPFRC(high-performance fiber reinforced concrete), Ferrocement, and UHPFRC(ultra-high-performance fiber reinforced concrete). Using these methods proved to increase the flexural capacity of the corroded beams and their structural behavior was improved. The specimen strengthened with HPFRC did not show any concrete cover crushing in the longitudinal rebars due to the good confinement action excreted in the high-performance concrete jacket. The drawback of this technique was after the ultimate load was reached the specimen suddenly started to lose its strength because there was no tensile strength contribution from HPFRC between the column base and foundation (higher cracks were noted). This method is also applicable for the beams to increase shear and flexural capacity by Alberto Meda[37]. It was seen special compactness and reduced crack opening characteristics of the HPFRC matrix this jacket acts as a protective layer for the existing column which was an effective method with a lot of surface preparation before application which is expensive. This patch repair of the RC structural element is more efficient for the element in critical corrosion level to increase its durability[50].

## 3.3 Evaluation of solutions based on material properties

FRP composites have several beneficial characteristics to be used in retrofitting of damaged RC beams like lightweight, non-corrosive, high tensile strength, well resistant to chemical and fungal attacks,  lower relaxation losses compared to steel. [ research paper]. Strengthening of corroded RC beams to improve the structural behavior led to the invention of new approaches. Several methods are frequently tested in strengthening corroded RC beams using FRP materials. Such common techniques using FRP are externally bonded (EB) system with laminates, near-surface mounted (NSM) with bars/strips. The special property of FRP is the low unit weight where CFRP is 5 times lighter than steel and the tensile strength using CFRP results in 8 to 10 times greater than steel. [ 2].

FRP materials cannot be used to strengthen the compression zone as they exhibit very low compressive strength. Their modulus of elasticity is low and is brittle. From the table above BFRP has good strain capacity compared to CFRP and GFRP. Although CFRP is preferred over GFRP and AFRP because of high stiffness properties. To be cost-effective GFRP is preferred over CFRP. GFRP strengthened structures have good ductile and residual strength compared to

CFRP which fails when the ultimate point is reached. In some cases when thermal resistivity is prioritized, BFRP materials are better than CFRP. Further research has to be carried out on the merging technique by using both CFRP and GFRP which can improve ductility, brittle failure, cost-effectiveness, etc., The flowchart below shows Fig. 7 the evaluations made on various FRP solutions based on material properties and the purpose of using FRP composites for strengthening.

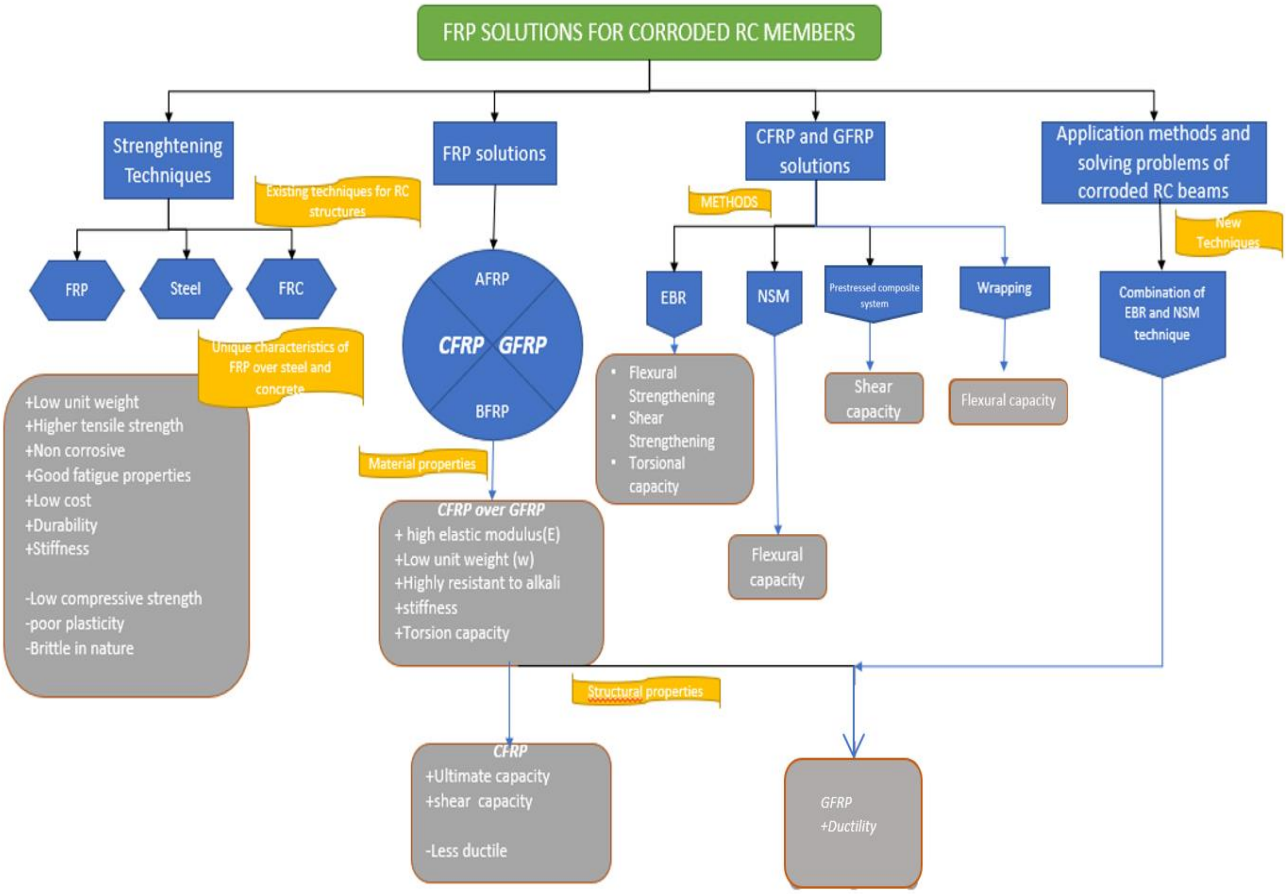


Fig:7 Evaluation of FRP solutions

# 4

# LITERATURE REVIEW ON FRP SOLUTIONS FOR FLEXURAL AND DUCTILITY RESTORATION

## 4.1 Methodology

The popularity and demand have emerged due to the need for maintaining and improving essential infrastructure in all parts of the world, together with the well-known advantages of FRP composites, discussed in previous chapters. The review work in the thesis is meaningful to the industry by providing the state of art FRP solutions studied in the latest research to strengthen the corroded RC structures. Based on the review work, various approaches were made to strengthen the corroded RC structures using FRP composites. Several approaches and methods have been followed from the past decades for strengthening the corroded RC structure to improve its mechanical and structural properties in service life. Based on the review of research papers most of the experimental research literature mainly focuses on the effect of steel corrosion on the flexural behavior of reinforced concrete elements.

### 4.1.1 Externally bonded reinforcement Technique (EBR)

From the review of literature on the topic repair and strengthening of corroded RC, beams show that researchers tried to overcome the drawbacks that occurred by strengthening without patch repair work. Most of the researchers compared the experimental results obtained by strengthening with and without patch repair work. The efficiency of the material and application technique was tested by Triantafyllou, Rousakis, and Karabinis[3] concluded that beams strengthened by the EB technique showed less deflection than the NSM strip method. Also, the efficiency of FRP material provided depends on the bond length rather than the number of layers used was experimentally testedand the failure modes were seendebonding failure of FRP at the mid and end span of the beam at ultimate load as shown in the Fig. (8)by Pham H and Al-Mahaidi R [4]. By considering the flexural behavior depending on the type of material used corroded RC beams were strengthened with GFRP laminates by Achudhan, Deepavarsa, and Vandhana Shalini [17] in 2019 which increased ultimate load capacity with high stiffness and strength. Improved service life with a significant increase in ductility. Triantafyllou [42] whereas the author concluded that at medium and high levels of corrosion, beams with patch repair work and strengthened with the EBR technique resulted in taking higher load which was almost twice the capacity when compared to

Fig: 8 Debonding of FRP strip[4]

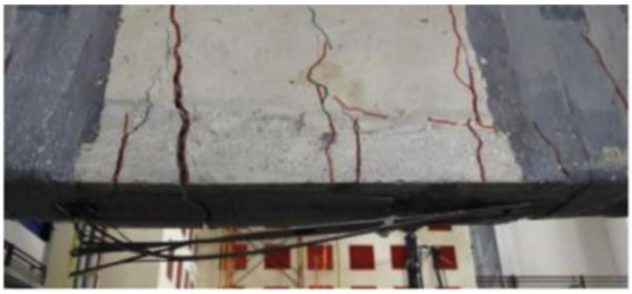


Fig :9 Cover crushing and debonding[42]

results from NSM technique.

At the ultimate loading, condition patch repaired EBR beam has failure modes,concrete cover separation, and debonding between the epoxy resin and CFRP strip as shown in Fig. (9). These are expected failure modes in EBR techniques which the authors concluded.

### 4.1.2 Near-surface mounted technique (NSM)

#### a) Near-surface mounted with FRP laminate strip

Garyfalia Triantafyllou et al. [1] - 2019 experimentally investigated the effectiveness of near-surface mounted CFRP strips in strengthening corroded RC beams at service load before and after patch repair work. Repair work was carried out before strengthening by the application of a corrosion inhibitor, and also an epoxy cementitious bonding agent was layered. During the experiment, several failure modes like concrete cover separation and debonding of epoxy-CFRP strips interface were examined. Then they concluded that patch repair work before strengthening was essential which restored the flexural capacity of the corroded RC beam. Triantafyllou G, et al. [3] studied the flexural behavior of corroded RC beams by comparing the results obtained by strengthening using both NSM and EBR techniques. Also, the efficiency of each method was tested before and after patch repair work by mechanical and air spray systems. From the experimental result, they concluded that beams strengthened by the NSM technique after patch repair work showed maximum load capacity than EBR. Yet at ultimate load, the disclosure of the NSM plate was observed leading to cover cracking as in Fig[10]. Also, beams showed more deflection by the NSM strip method compared to externally bonded. Triantafyllou [42]experimented to check the most effective method in strengthening corroded RC beams between NSM and EBR techniques. The author also tried to formulate and compare the result before and after patch repair work. The beams were subjected to low, medium, and high levels of corrosion with different percentages of steel mass loss. removal of damaged concrete and brushing the reinforcement to remove the corrosion debris applying corrosion inhibitors patching the concrete with respective cover depth. The experimental results from all three levels of corrosion were concluded as beams with a low level of corrosion up to 10% strengthened with the NSM method resulted in taking a maximum load. NSM strips exhibited reduced efficiency in beams with medium and high levels of corrosion. With breakage of tensile bar leading to back face cracking as shown in Fig[11]resulted in NSM fracture. The effect of shear wrap on NSM strips was lower as the additional anchoring effects are expected to be weak inside the concrete slits and rather enhance the bond old concrete patch interface. Triantafyllou [43] studied the load-carrying capacity of strengthened corroded RC beam before, and after path repair, two beams electrically corroded up to 25% were repaired one beam was repaired with NSM CFRP strip bonding directly to concrete another beam the cracked concrete cover was removed and the steel rebars were treated. The cement-based repair mortar and two NSM FRP laminates were applied to both beams and were tested to failure. From the results at high corrosion level before repair and strengthening -high deflection Repair work has restored the load capacity. The beam with a maximum loss of steel resulted in taking less load. Pitting corrosion and local corrosion in the reinforcement was the main cause of tensile deformability.

Fig : 10 Disclosour of NSM plate after cover crushing[3]

Fig: 11 Rupture of corrosed tensile bar back face crack[42]

**b) Near-surface mounted with FRP Rods**

Belal Almassri et al. [6] carried out the experimental tests for the flexural behavior of naturally corroded beams strengthened by NSM- CFRP rods. They concluded that flexural capacity and ductility were increased and they mentioned the NSM technique is the most common and effective than externally bonded. Almusallam T et al. [10] experimentally researched on flexural behavior of corroded reinforced concrete beams strengthened using NSM-GFRP bars. Both analytical and finite element modeling analysis was carried out for 16 beams grouped and tested under a four-point loading system. Then the result showed an increase in flexural capacity with an increase in stiffness. The deformation on the tensile bar resulted in cover separation which was a failure mode observed as shown in Fig. [] Also, they confirmed from an investigation that the capacity could be further increased with an increase in the GFRP reinforcement. Almassri B, Kreit A, et al. [14] 2014, experimentally found the mechanical behavior of corroded RC beams strengthened by NSM technique. CFRP rods were grooved along the tension face of the beam. The authors found that stiffness was increased between the reinforcement and concrete which increased load-carrying capacity.Fig. [] shows cover cracking of concrete at maximum loading due to a larger strain steel bar. They also concluded that the NSM strengthening technique with CFRP rods made the structure more ductile. Belal Almassri [44] performed an experimental and numerical analysis to examine the behavior of corroded RC beams strengthened with NSM CFRP rods loss of steel in the beam was 20% on average from the left edge of the beam and at the top of the bars close to the surface cover, an experimental test was made by making two groove cuts in the concrete cover in the longitudinal direction at the tension side and placing CFRP rods bonding with resin-filled up to surface level. Concrete crushing, pull-out of the FRP rods, or peeling-off this is due to the separation of concrete cover. the results indicated the NSM technique restored significant ductility by avoiding premature failure of tensile bars at pit locations. In FEM analysis, reduction of ultimate deflection of non-repaired beams due to the more brittle behavior of corroded steel in tension but could not capture the ductility recovery induced by the repair with NSM rod.

### 4.1.3 Wrapping Technique

Repairing of corrosion damaged concrete cover using CFRP bonding in the tension side after concrete cover patch repair by removal of spilled concrete and patching it with concrete by Saidy and Al-Jabri is an effective the specimen was able to reach ultimate loads higher than the ultimate load of damaged state. replacing the damaged concrete cover with a new layer of concrete before strengthening is more effective in load transfer mechanism between FRP and concrete, U-shaped CFRP anchorage wrap enhances the structural performance of the element [20].Tamer Maaddawy et al [7] researched in an extension of the service life of the corroded reinforced concrete beams strengthened by carbon fiber reinforced polymer wrapping. They wrapped the laminates both in longitudinal and transverse directions. Few beams were strengthened by wrapping continuously along the longitudinal direction and few beams with intermittent wrapping. The authors also specifically investigated the effectiveness of increasing the number of laminates wrapped for strengthening. They concluded that the beams wrapped continuously along the middle span showed higher strength than beams wrapped with intermittent spacing. Also, researchers found a decrease in deflection by this technique which could be more improved with an increase in the number of layers laminated around. The observed modes of failures under the wrapping technique was debonding of FRP laminates and FRP rupture Fig. (12 &13). Khaled A Soudki et al.[13] in 2002 research on the strengthening of corroded reinforced concrete beams by fiber-reinforced polymers. The researchers experimentally tested by the U-wrapping technique using both glass and carbon polymers. The corroded beams were strengthened without patch repair work. They also noticed an increase in mass lass percentage from 2.5% to 12% which they concluded to be the cause for failure. Ahmed Abdel et al. [18] evaluated several structural properties like load carrying capacity, deflection, and ductility by strengthening the corroded reinforced beams using CFRP U-wraps. They experimentally tested with the self-compacting concrete (SCC) which was corroded up to 50% mass loss. Using this wrapping technique the authors tried to compare the results of load capacity before and after patch repair work.They concluded that nearly 57% of the load-carrying capacity of the beam was lost by strengthening without patch repair work. So they proved from the experimental result, patch repair work is efficient to restore the load capacity of the corroded RC beams.They finalized that the beams tested with patch repair work could restore load capacity up to 42%.

Fig : 12 Debonding of FRP laminate [20]

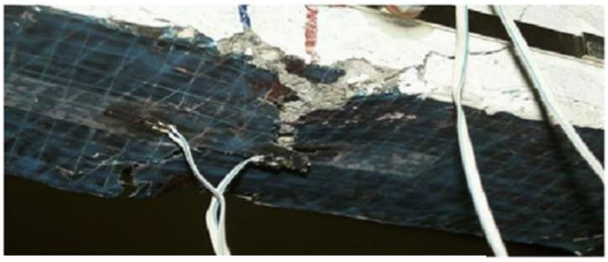


Fig : 13 FRP laminate rupture[20]

Jian Hui Li et al. [29] researched on bond behavior of corroded reinforcing bars in concrete wrapped with CFRP sheets. The researchers experimentally tested and studied the effectiveness of wrapping/confinement technique between corroded and normal concrete beams wrapped with CFRP sheets Researchers found that within 5% mass loss of steel, the ultimate bond strength was increased with the reduction of bond stress. Also, they noticed a change in the mode of failure from brittle concrete splitting to ductile bar pullout as shown in Fig. [14] below. Rajan sen [30] in 2003 studied the advances in the application of this wrapping technique for repairing the damage caused by corrosion. The researcher had done several reviews and research works were carried out in finding the effective technique of FRP wrapping. El Maaddawy T et al. [32] in 2005 worked on computer-based mathematical models and studied the structural behavior of corroded beams repaired with fiber-reinforced polymers. They also made comparisons between the results obtained from mathematical modeling and experimental tests. They experimented by wrapping the corroded beams under two schemes such as continuous and intermittent wrapping. From the comparison of test results, they concluded that the designed mathematical model determined the most accurate values compared to the experimental results. The authors named the computer program designed as ACFRP (Analysis of corroded and FRP repaired beams). Saidy Jabri et al. [33] in 2011 experimented on the structural performance of corroded RC beams which were repaired with the CFRP wrapping technique. They tried strengthening the corroded RC beams under three different schemes. Under scheme-1, they wrapped the sheet continuously along the tensile face of the beam. The authors improvised this scheme and added additional U straps at the tension side. Under scheme 3, they wrapped the beam along both longitudinal and transverse sides. Finally, they concluded that the beams strengthened with U wraps restored the maximum strength and confirmed to be most effective.Nameer A Alwash et al. [35] in 2019 studied experimental results by an external strengthening of corrosion defected members using CFRP wrapping technique. They U-wrapped on the surface of the corroded beams which were subjected to different levels of corrosion.Test results showed that the effect of CFRP U wrapping restored the load-carrying capacity which increased stiffness and serviceability.

Figure 8 Failure mode- Bar pulloutref -29

## 4.2 Effect of patch repair work on  Flexural behaviour

Garyfalia Triantafyllou et al. [1] - 2019 experimentally checked the effectiveness of patch repair work before strengthening the corroded RC beams using NSM-CFRP rods.  This is attributed to a significant cross-section reduction caused by the extensive corrosion and loss of bond between the concrete cover and steel reinforcement, as was observed after the removal of the damaged concrete cover. Beam with the third level of corrosion with 24.42% of steel loss patch repaired with  NSM(BC3-60 NSM) that was subjected to 60% service load even after repair with the NSM strips, presented a cracking load of 10.6% which is lower than the non-corroded beam. The yielding load was 25.2% lower than that of a non-corroded beam due to the steel cross-section reduction resulting from the induced corrosion. Fig. 15 and 16, that the patch repair and NSM strengthening could improve the ultimate capacity of BC3-60 NSM, where the maximum load increased by 3.3% (256 kN) at the deflection of 20.4 mm compared to the reference beam which is a non-corroded beam 205 KN. Longitudinal cracks at the interface of the old concrete substrate and the patch repair concrete were observed only after the yielding of steel in tension. Beam with the third level of corrosion with 30.7% of steel loss patch repaired with  NSM (BC3-75) was intensively cracked over the entire length, and tensile reinforcement was severely corroded. The ultimate load at debonding was 272 kN at the deflection of  27.7 mm. This is a 9.8% higher load compared to the non-corroded beam with and 6% higher compared to the BC3-

60 NSM strengthened beam with the lower service load but with equivalent axial rigidity FRP reinforcement. Although patch repair work before strengthening has been carried out recently by most of the researchers. Triantafyllou G et al. (3) had tested the effectiveness by strengthening the corroded RC members using FRP laminates before and after patch repair work. beam RC-COR1S1 strengthened with CFRP EBR after the patch repair with a corrosion level of 6.18% subjected to loading until failure, the yield load of 156 KN was seen which is 6% higher than non-corroded beam and 14% more than the corroded strengthened beam. the presence of flexural CFRP laminate improved the stiffness compared with a non-corroded beam. and RC-COR1S2 strengthen with CFRP NSM after the patch repair with a corrosion level of 6.05% subjected to loading until failure. the first cracks due to flexural were observed at a load of 57 KN, which is 2 times greater than the non-corroded beam. During the cracking, the initial crack did not extend till the epoxy adhesive filled in the groove because the tensile strength and ductility of the adhesive are higher than concrete. The beam yielded at a load 153kN, 6% higher compared to the uncorroded beam, and 12% higher compared to the corroded unstrengthened beam. When the load reached 183 KN, a longitudinal crack in the the interface between the old and the new repair mortar opens up in a parallel direction. This crack opened further when the load was equal to 198.4kN. NSM CFRP strengthened beam presented a significant increase in the load-carrying capacity and deflection when compared to the EBR strengthened beam.

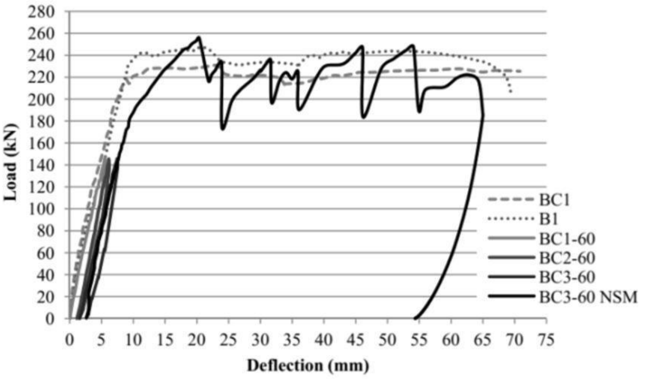


Fig: 15 Load deflection curve for patch repaired beam NSM loaded 60% [1]

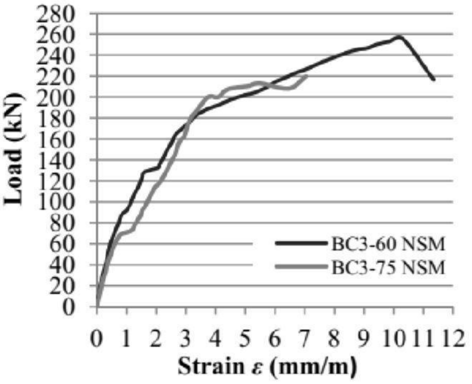


Fig :16 Load deflection cure of strengtheind beam compared with 60% and 75% loading[1]

Balamuralikrishna R et al. (39) They carried out the work by using two different material laminates like GFRP (Glass fiber reinforced polymers) and CFRP(carbon fiber reinforced polymers ). Since they calibrated the corrosion level was too high up to 50% of steel mass loss, the cracks formed were also huge. The corroded portions were sandblasted and removed. They sealed the cracks with epoxy and then the laminates were bonded along the tension face of the beam. when the beams were tested, beam with 10% corrosion level patch repaired and strengthened resulted in gaining 50%, 25%, 40%, and 25% increase in strength concerning reference beam at a first cracking stage, serviceability load, yield load, and ultimate load respectively. This increase in load-carrying capacity is due to an increase in the tensile cracking strength of concrete is due to the bonding or GFRP laminated to the corresponding beam section (larger moment of inertia of the section). the author says the bonding of GFRP laminates to the section has a positive effect on the beam from the initial cracking stage. the beam with 20% steel loss when test untile failure exhibits a decrease of 5%, 33%, 34%, and 33% in strength concerning non-corroded beam at all the four stages .i.e. first cracking stage, serviceability load, yield load, and ultimate load respectively. This is due to the insufficient tensile strength of the section because of the large reduction in tensile steel reinforcement. But, there was an increase in strength up to 69% in the strengthened beam concerning the corroded beam. the beam with high corrosion level up to 30% and 40% steel loss displayed a raise of 2.5 to 9 times in load-carrying capacity when to corresponding corrosion damage beam. Triantafyllou G et al. (42) Experimental test was carried out for the beams which were subjected to three different levels of corrosion from low(7.5%) medium(15.5%) and high(24%), the beams were patch repaired and strengthened using CFRP EBR and NSM techniques. Table (2) below shows the experimental results RC-COR1 (low corrosion level), RC-COR2(medium corrosion level), and RC-COR3(high corrosion level). It is seen that the beams strengthened with NSM patch repair showed good flexural strength at low corrosion level compared to EBR, nevertheless, EBR patch repaired exhibited very good flexural capacity at medium and high corrosion level at maximum and ultimate loading conditions.

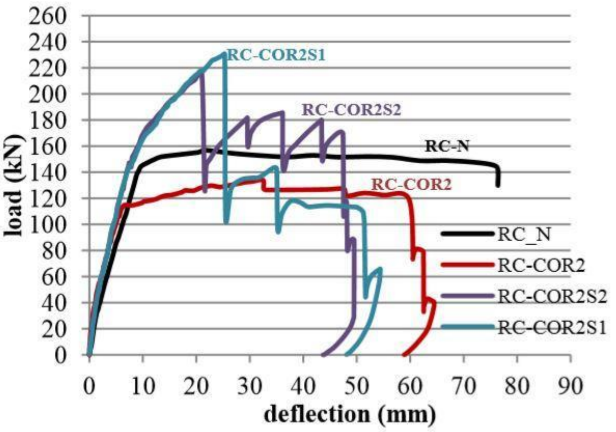


Fig: 17 Load deflection for SM patch repaied for medium corrosion level [42]

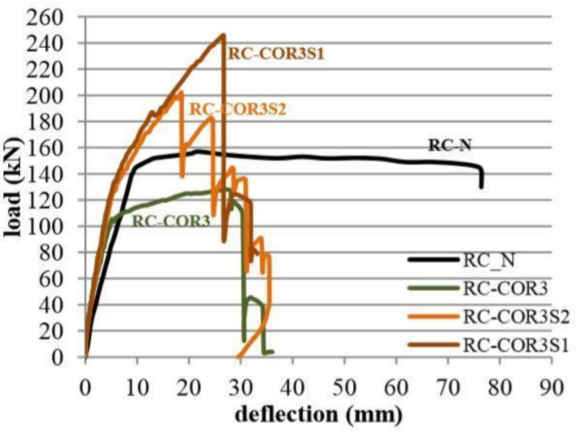
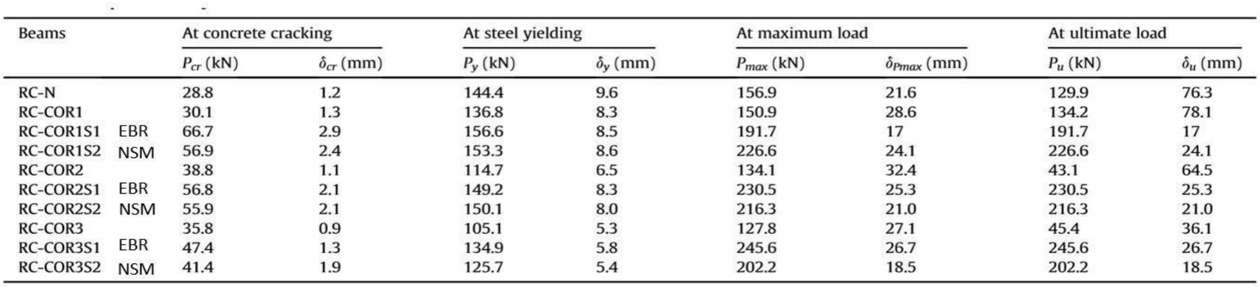


Fig: 18 Load deflection for SM patch repaied for high corrosion level [42]



| Beams | | At concrete cracking | | At steel yielding | | At maximum load | | At ultimate load | |
|---|---|---|---|---|---|---|---|---|---|
| | | $P_{cr}$ (kN) | $\delta_{cr}$ (mm) | $P_y$ (kN) | $\delta_y$ (mm) | $P_{max}$ (kN) | $\delta_{Pmax}$ (mm) | $P_u$ (kN) | $\delta_u$ (mm) |
| RC-N | | 28.8 | 1.2 | 144.4 | 9.6 | 156.9 | 21.6 | 129.9 | 76.3 |
| RC-COR1 | | 30.1 | 1.3 | 136.8 | 8.3 | 150.9 | 28.6 | 134.2 | 78.1 |
| RC-COR1S1 | EBR | 66.7 | 2.9 | 156.6 | 8.5 | 191.7 | 17 | 191.7 | 17 |
| RC-COR1S2 | NSM | 56.9 | 2.4 | 153.3 | 8.6 | 226.6 | 24.1 | 226.6 | 24.1 |
| RC-COR2 | | 38.8 | 1.1 | 114.7 | 6.5 | 134.1 | 32.4 | 43.1 | 64.5 |
| RC-COR2S1 | EBR | 56.8 | 2.1 | 149.2 | 8.3 | 230.5 | 25.3 | 230.5 | 25.3 |
| RC-COR2S2 | NSM | 55.9 | 2.1 | 150.1 | 8.0 | 216.3 | 21.0 | 216.3 | 21.0 |
| RC-COR3 | | 35.8 | 0.9 | 105.1 | 5.3 | 127.8 | 27.1 | 45.4 | 36.1 |
| RC-COR3S1 | EBR | 47.4 | 1.3 | 134.9 | 5.8 | 245.6 | 26.7 | 245.6 | 26.7 |
| RC-COR3S2 | NSM | 41.4 | 1.9 | 125.7 | 5.4 | 202.2 | 18.5 | 202.2 | 18.5 |

Table:2 Results for patch repaired EBR and NSM beams [42]

On the other hand, the deflection was lower at maximum and ultimate load in NSM at the high level of corrosion compared to EBR this implies the EBR technique is good for restoring ductility in a beam. it was concluded that the EBR technique is ideal to increase flexural capacity and restoring ductility at a medium and high level of corrosion. whereas the NSM technique is more effective in strengthing beams with lower corrosion level. The above Fig.(17) and Fig (18) indicates the various beam behavior at different loading conditions after strengthening in terms of load versus deflection.A.H. Al-Saidy and K.S. Al-Jabri[20]investigated experimentallythe effect of patch repair on strengthening corroded beam with CFRP sheet claimed that the patch repair work reduces the strain the corroded steel. Patch repair is done to gain a proper bond with parent material and to avoid further corrosion in the future. Fig (19) shows the strain level at various levels of the section the strain at steel is less compared to FRP at loss corrosion level which is 5%, in this case, the steel is on the safe side and patch repair is not necessary at low corrosion level. bond stress is less in a corroded beam It is assumed that all the components of the beam that are concrete steel and FRP act one ideal unit under flexural stress the strain across the depth of the section must

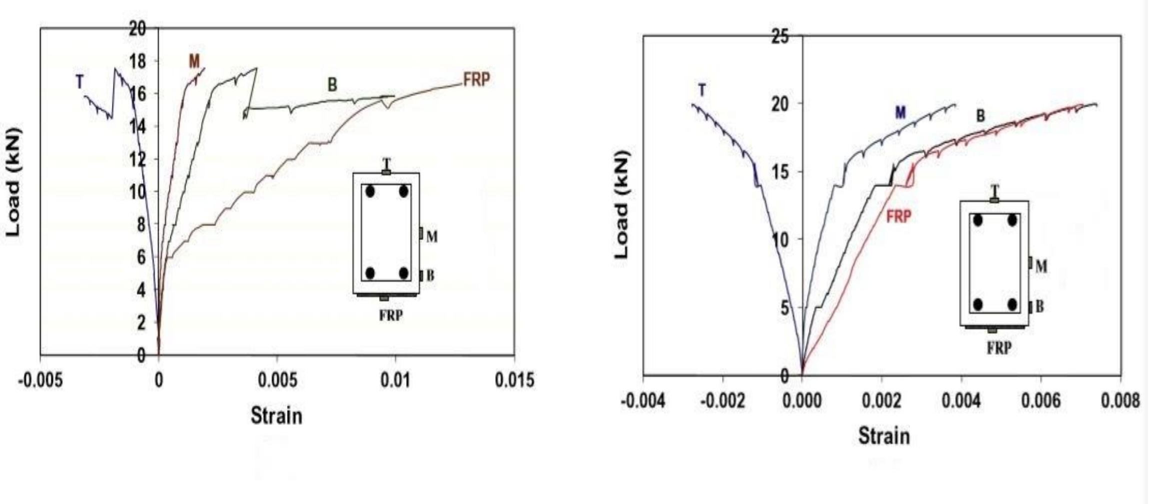


Fig:19(a)Strain at various section without patch repair 5%steel loss (b) Strain at various section with patch repair 5% steel loss[20]

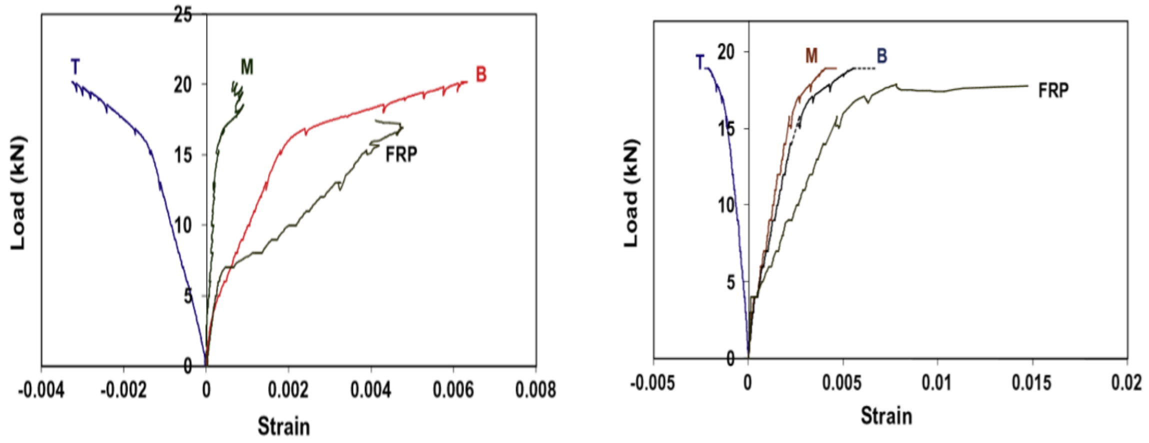


Fig: 20(a)Strain at various section without patch repair 8%steel loss (b) Strain at various section with patch repair 8% steel loss[20]

be linear which can be seen in Fig (19).this is attained in a patch repaired beam. In Fig (20) the strain steel is higher than FRP at further loading the steel breaks and there will be FRP rupture which is one of the failure modes. On the other hand, the beam patch repaired and strengthened results with linear behavior in all the sections of the beam which means there is a full composite action on FRP and concrete section. due to corrosion But after the patch repair[20]

## 4.3 Evaluation of corrosion level and Flexural behavior after strengthening

### 4.3.1 Low levels of corrosion

After patch repairing the corroded beams and strengthening with NSM CFRP strips Garyfalia Triantafyllou et al. (1) in 2019 analyzed carried out experimental work on RC beam corroded under accelerated electrochemical technique to a smaller corrosion level subjected to vertical service loads in the first phase of the experiment(one corrosion cycle) after the test the beam was subjected to the next corrosion cycle for 16 days and tested this study approach is a perfect example to know post behavior of beam after strengthening and its progressive behaviors at every stage the efficiently restore the capacity of corroded concrete beams. The residual bearing load after CFRP debonding depends on the different localization of damages throughout loading in beams with different mass loss of steel rebars due to corrosion. Even in the case of tensile steel bars yielding, the proposed retrofit was successful. Yet, localization of damage and pitting corrosion should be thoroughly investigated in any case as it can significantly reduce the tensile deformability of steel. Triantafyllou G et al. (3) conducted a test for a beam with an average gravimetric mass loss of corrosion of about 10%. The accelerated corrosion process included placing beams inside a tank which contained an industrial salt solution of 3% concentration to achieve uniform corrosion throughout the beam. The rate of mass loss of tensile bars was regarded as a corrosion rate and was calculated using Faraday’s law. The patch repaired beam strengthened with CFRP NSM exhibited an improved flexural capacity of 18.2% and a higher deflection of 41% from before. Triantafyllou G et al. (42) accelerates the corrosion process, the beams were partially immersed inside a tank with 3% industrial salt solution and were subjected to a constant current density using power supplies the tensile bar was connected to the power supply and with the phenomenon of Faraday's law, three different durations 8, 16 and 24 weeks of impressed current were applied to achieve three different degrees of corrosion 7.5% to 10 %, the corrosion percentage was calculated as an average percentage of steel loss throughout the beam. Debonding and concrete cover the separation mode of failures. The debonding failure was between the epoxy and CFRP strip interface. From this strengthening technique, the authors concluded that the restoration capacity of the corroded beams improved and confirmed this to be an efficient method in strengthening the corroded beams with patch repair work.

### 4.3.2 Medium level of corrosion

Belal Almassri et al. (6) exposed RC beams for natural corrosion for 25 years the value of percent loss of steel (corrosion percentage) was calculated by measuring the diameter of the corroded rebar both front side and the base side of the tensile bar. The maximum diameter loss was found to be 38% from the left edge of the beam. The corrosion was found both at the top of the bars close to the surface cover and the base of the bar Fig. (21)this type of corrosion is the outcome of classical natural corrosion, a graphical study was made to determine the average corrosion along the length of the beam by plotting graph length of the beam versus the average percentage of steel loss this gave a clear idea about the loss of steel at different points of the beam it was seen that an average of 20% of mass loss at the mid-span of the beam it was assumed that the yielding of steel takes place at mid-span. This study is a work of art that explains post requirements for strengthening the number of layers of FRP to be bonded to gain strength at a particular location of the beam. The NSM method used to repair corroded RC elements were able to restore significant ductility by avoiding the early failure of tensile bars at corroded locations.

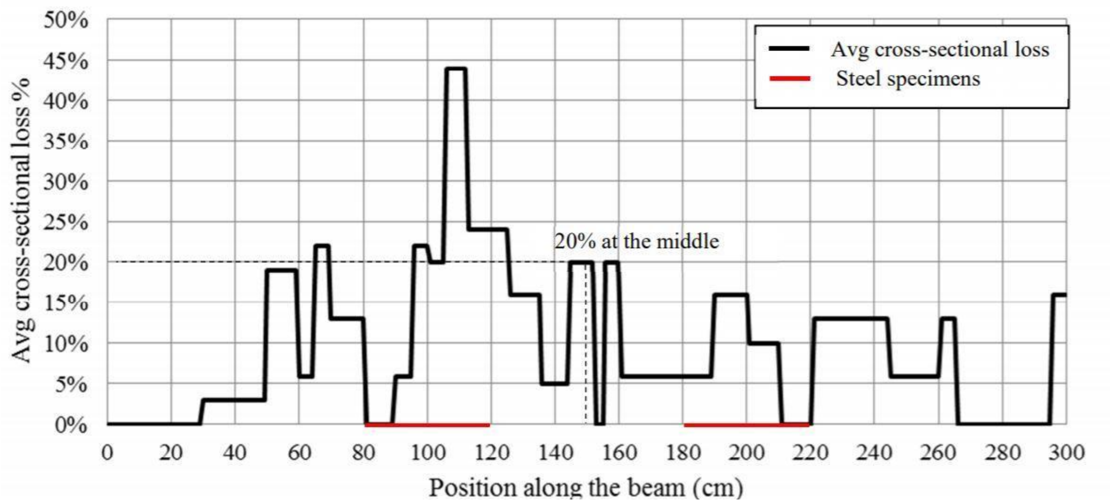
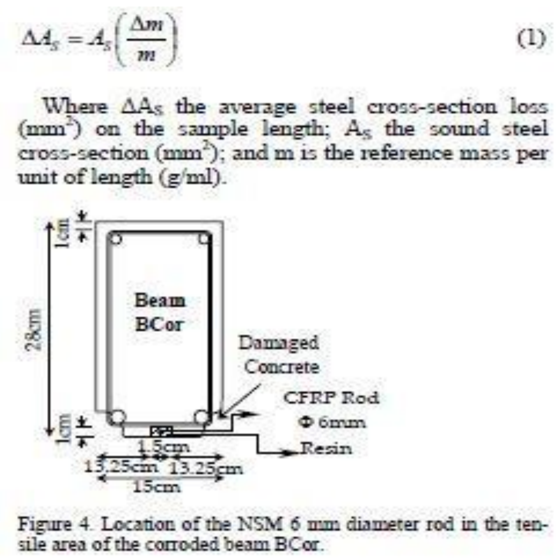


Fig: 9 Average percentage of steel loss along the corroded beam[6]

Tamer El Maaddawy et al. (7) patch repaired the corroded reinforced beams by surface sandblast method and they washed away the residue. The percentage of mass loss was calculated and they mentioned to be around 31%. Researchers strengthened the beams using CFRP wrapping technique where they laminated and provided wraps with continuously wrapping and also by intermittent wrapping techniques. They concluded that this method resulted in less deflection. The experimental results showed improvement in flexural strength when the beams were wrapped continuously along the middle span.

Tamer El Maaddawy et al. (7) presented a flexural analysis of corroded RC beams which were strengthened by carbon-reinforced polymers using a wrapping technique. They experimented by subjecting 11 beams to corrosion by impressed current technique. The maximum loss of steel was up to 31%, which was calibrated and measured using Gravitational mass loss technique. Out of 11 beams, a brief comparison was made where they strengthened and repaired for only 6 beams. They compared the experimental results with the remaining 5 corroded un-strengthened beams. Due to high levels of corrosion, they used a sandblasting method which then washed and cleared out the corroded substrate. Authors showed that the beams which were corroded up to 31% steel mass loss and repaired by the CFRP technique had increased load capacity up to 73% when they compared with the corroded unrepaired beams. They also checked the amount of deflection that the repaired beams showed, and they concluded from the comparison that the CFRP repaired beams showed very less deflection up to 46% lower than corroded unrepaired beams.

Amjad Kreit et al. (15) in 2009 established a theoretical formula in calculating the percentage of steel mass loss due to subjected corrosion. They evaluated the corrosion loss damage where they completely removed the corroded concrete part. The removed corroded mass was calculated using Clark’s solution. Also, the authors tried to measure the corroded part with a reference mass of reinforcement in the uncorroded beams. They used the below formulative relationship Fig. [22] between average steel cross-section loss and sample length to calculate the average corroded mass of steel reinforcement.



$$\Delta A_S = A_S\left(\frac{\Delta m}{m}\right) \quad (1)$$

Where $\Delta A_S$ the average steel cross-section loss ($mm^2$) on the sample length; $A_S$ the sound steel cross-section ($mm^2$); and m is the reference mass per unit of length (g/ml).

Figure 4. Location of the NSM 6 mm diameter rod in the tensile area of the corroded beam BCor.

Fig: 10 Clarks solution and placement of NSM bars for the corroded beam -ref (15)

Authors concluded from the NSM CFRP strengthening technique had significantly increased the bearing capacity and also they mentioned this technique to be very efficient since they resulted in the ultimate capacity obtained from the corroded repaired beam was almost equal to the ordinary reference uncorroded beam. They also measured the ultimate deflection from the repaired beam and found it to be lower than the ordinary beam. Huifeng, jin Wu and Chengjun (19) subjected beams for accelerated corrosion by accelerated corrosion devices. which consists of a DC power, and stainless steel cathode, immersed in the 5% NaCl solution the beam specimen is immersed in the solution and power is passed for 14 days. the percentage of loss of steel was calculated using Faraday's law as per the results obtained the beams were characterized to different percentage levels 5% 10% 15 % and so on it was observed loss of steel was maximum at the mid-span of a beam. Considering the patch repair work before strengthening with FRP material for the beams subjected to different levels of corrosion are experimentally tested by Triantafyllou G et al. (42) in 2018. Here authors discussed the importance of removing the corroded substrate. They conducted pull out tests to calculate the tensile strength at different locations of the corroded beams. From the results, they removed the concrete substrate up to the entire diameter of the tensile longitudinal reinforcement for the medium and high levels of corrosion. Later they washed away the corroded substrate by a mechanical method and they applied the inhibitor which prevented corrosion.

### 4.3.3 High level of corrosion

Ahmed Abdel and Hui Shen (18) studied the strength restoration capacity for the corroded reinforced concrete beams that were subjected to high levels of corrosion. They experimentally conducted a small scale corrosion test to determine the relationship between the amount of mass loss of steel reinforcement due to corrosion and an electric current passed for corrosion. They carried out the macroscopic galvanic study to corrode the steel reinforcement and the arrangement is shown below Fig.[23],[24]. They followed the chemical method to corrode the steel reinforcement by adding NaCl salt solution and the current was supplied which connected steel to the positive terminal and copper to the other.

Figure 1. Small corrosion test setup.

Fig :23 Sample of rebar for corrosion ref (18)

Figure 2. Rebar sample after corrosion.

Fig :24 Corroded sample ref (18)

They used this same technique for the corrosion of steel reinforcement in the large scale. The steel bars were continuously subjected to corrosion for several days until they reached their experimental target study for the corrosion level. Similar procedures which they followed in small scale corrosion tests were used to determine the target percentage of mass loss. They mentioned the number of days it took to reach the maximum targeted 50% steel mass loss. Fig. [25], [26] shows the details of experimental work researchers done in the large scale corrosion process.

Figure 4. Actual corrosion test setup.

Fig:11 Experimental steup for Electric corrosion- Ref(18)

**Figure 6.** Steel rebars are corroding during the test.

Fig:12 Rebars under c

orrosion ref (18)

Later they repaired and strengthening work by providing CFRP sheets for a few of the corroded RC beams as shown in Fig. [27]. A brief comparison study was carried out between strengthened and un-repaired corroded RC beams. They U wrapped CFRP sheets for the beams with a maximum 50% mass loss of corrosion. The installation method of the CFRP sheet is shown below.

Fig:13 Repaired and strengthened beam with CFRP sheets Ref( 18)

The authors concluded that the level of corrosion had not affected the cracking load. Also, beams with 50% corrosion level without patch repair work were not able to restore the load capacity and they mentioned those beams showed 56% less capacity in taking load with very low stiffness. Later they specified these beams with patch repair work had improved the capacity of up to 42%. Finally from the experimental test results for various levels of corrosion, they examined that beyond 20% mass loss strengthened with CFRP sheets were not effective for the full restoration of load capacity. Finally, they made a statement in the conclusion that the strength, restoration capacity, and stiffness depends on the level of corrosion.

The effectiveness of repair and strengthening techniques for the beams subjected to high levels of corrosion was investigated by Su Linwang et al. (36) in 2015. They studied the flexural behavior of corroded concrete beams repaired by CFRP sheets which were damaged to different levels of corrosion. They carried out a comparison test study between the beams strengthened directly with CFRP sheets and the beams strengthened after patch repair work or surface preparation. They had set up an experiment and corroded 5 beams at different levels Fig. [28] through an accelerated corrosion process. They calibrated the percentage of mass loss from the crack widths developed and they classified as below

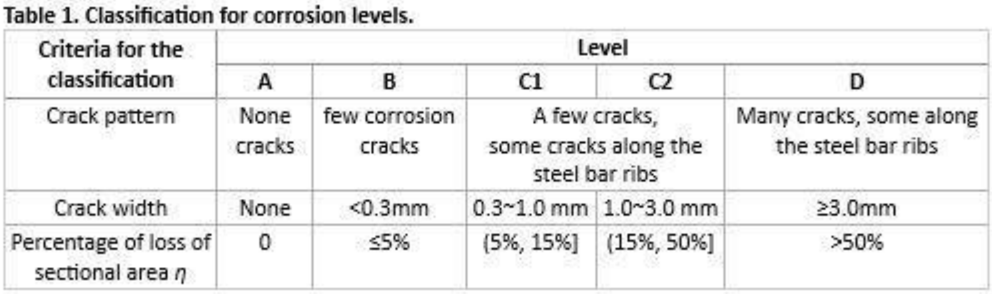


**Table 1. Classification for corrosion levels.**

| Criteria for the classification | Level | | | | |
|---|---|---|---|---|---|
| | A | B | C1 | C2 | D |
| Crack pattern | None cracks | few corrosion cracks | A few cracks, some cracks along the steel bar ribs | | Many cracks, some along the steel bar ribs |
| Crack width | None | <0.3mm | 0.3~1.0 mm | 1.0~3.0 mm | ≥3.0mm |
| Percentage of loss of sectional area $\eta$ | 0 | ≤5% | (5%, 15%] | (15%, 50%] | >50% |

Fig:14 Classification based on crack pattern, crack width and percentage of steel mass loss due to corrosion- ref (36)

The maximum loss of mass steel reinforcement was calculated and was about 69.84%.Also, they plotted a graph which defined the mass loss due to corrosion is shown below, they measured it through a general method and used a vernier caliper instrument to measure the exact cross-section as shown in Fig. [29]

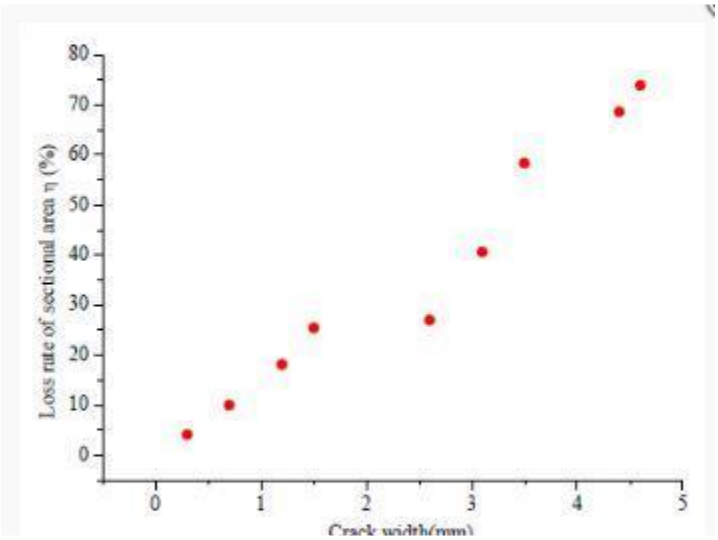


Fig: 15 Vernier calipers method to measure the loss of sectional area ref (36)

Also, they clearly explained the influence of strengthening for different levels of corroded beams with 2 different strengthened methods. From the result plotted belowFig. [30] concluded that the beams with higher levels of corrosion showed higher deflection. Finally, they concluded that the beams strengthened with CFRP sheets showed improvement in bearing capacity and stiffness when compared to unstrengthened beams. This made the authors conclude that the strengthened beams are less ductile and ductility reduced when compared to unstrengthened beams.

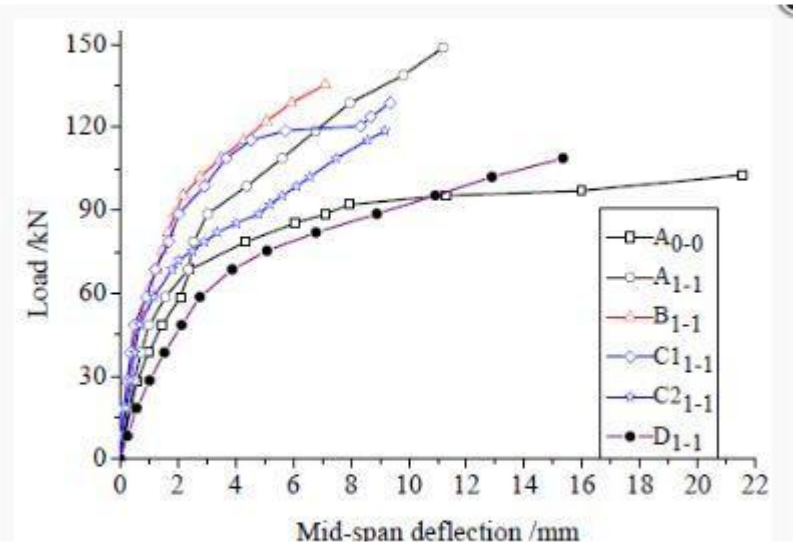


Fig: 16 Graph plotted to explain the influence of strengthening ref(36)

To improve the serviceability condition for the damaged structures, Balamuralikrishnan R and Thirugnanasambandam S (39) in 2016 rehabilitated the corroded reinforced concrete beams using two different materials like GFRP of 3mm thick laminates and also with CFRP laminates. Authors specified repair is an important factor for the corroded beams in extending the lifespan of structures. They carried out patch repair work with the removal of corroded substrate, blew away the rust, washed away the residues then they used patch material and fixed the original geometry lost due to corrosion. They also identified that the cement-polymer mortar has better adhesive properties,crack resistibility, and compatibility when compared to the cost and other material properties. So they had chosen Styrene-butadiene rubber (SBR) latex and repaired the corroded geometry. 30%, 40%, and 50% of corrosion damaged beams were repaired. For the beams with the high level of corrosion up to 50%, they removed the cover concrete and remolded with the new polymer, also they added tensile reinforcement and then they bonded with CFRP and GFRP laminates for the experimental tests. From the experimental results, authors concluded that FRP cannot exhibit its effectiveness in strengthening the beams which were corroded to a high level. They also mentioned the load-carrying capacity decreased for the beams with higher corrosion when they strengthened with FRP laminates. They studied other mechanical behavior of structures like deflection, stiffness, and ductility. From the experimental results, they found the CFRP strengthened beam ended with poor ductility, but the deflection was improved.

## 4.4 Interesting facts from the review

- Prestressing the NSM-GFRP technique could avoid early failure of rupture or debond.
- The efficiency of FRP depends on bond length rather than the number of layers.
- Installing FRP with epoxy resin is more effective than using inorganic material like cement mortar.
- Ductility decreases with an increase in mass loss percentage.
- Patch repair work is very effective in increasing the ultimate load capacity.
- Patch repair work prevents further increase in corrosion with an increase in stiffness.
- Beams strengthened with GFRP wraps are more effective in reducing further corrosion than CFRP wraps.
- Confinement using CFRP sheets changes the mode of failure from brittle concrete splitting to a ductile bar pullout.
- Brass coated with hooked fibers (BHFRC) showed the highest flexural strength when compared to glass fibers and other composites whereas beams strengthened with GFRC-glass fiber reinforced composites resulted in reduced strength but improved ductility.

# 5

# MOTIVATION FROM REVIEW FOR PROPOSED SOLUTION

## 5.1 Methodology

Several solutions are existing in strengthening corroded RC structures. The common techniques using FRP are near-surface mounted (NSM) with bars/strips and externally bonded (EB) systems with laminates. In very few cases mechanical anchorage systems and grooving methods with or without adhesives are used. Garyfalia Triantafyllou et al. [1] indicates that the strengthening of corroded RC beams with NSM CFRP strips, having identical FRP reinforcement but under application of different service loads, resulted in different structural behavior and failure modes. The failure mode of both corroded strengthened beams is mainly characterized by concrete cover separation, and debonding of the epoxy-CFRP strips interface. FRP strengthening with patch repair can efficiently restore the capacity of corroded concrete beams. The residual bearing load after CFRP NSM debonding depends on the different damages throughout loading in beams with different mass loss of steel rebars and stirrups due to corrosion. Triantafyllou [42] reflects the failure mode such as the rupture of CFRP laminates in the bending area after tensile steel can contribute to severe corrosion damages in stirrups. Reinforced concrete beams that get deteriorated due to chloride attacks have been strengthened with various techniques for several years. Corroded beams need to be strengthened to increase their flexural strength, shear strength, fatigue life, and also to improve the ductile nature of the structure. Repair and strengthening of corroded and damaged reinforced concrete beams had been challenging for all engineers in the construction field.

## 5.2 HYBRID/FUSION METHOD (OUR COMBINED SOLUTION)

One of the main factors that govern the corroded strengthened beam is a type of failure mode. Some of the most common methods used are EBR and NSM with different types of materials like carbon, steel, glass, etc Both techniques have their limitations in mechanical behavior. Some of the researchers mentioned externally bonded reinforcement (EBR) technique is effective in improving the ultimate flexural capacity of the beam, but showing earlier debonding failure. whereas, Near-surface mounted (NSM) has helped in the restoration of ductility and has limitations where the beam fails due to concrete crushing or concrete cover separation. More recently, near-surface mounted technique (NSM) has attracted an increasing amount of research as well as a practical application because it is less prone to premature debonding. By studying through different research works, we considered an infusion of EBR and NSM techniques as a hybrid technique. By using steel plates and steel bars professor Prabhakaran and a post-graduate student Megha Joe had experimentally investigated the behavior of reinforced concrete beams flexural strengthened with combined EBR and NSM technique. The presence of high interfacial shear stresses at the end of the externally bonded plate may reduce the resistance to failure of the strengthened structure. Also, the application of NSM is limited due to the absence of sufficient width and a clear cover of the existing unstrengthened deficit beam.[46].They used steel bars in the NSM technique and steel plates for the EBR method. The below figures explains the experimental set up as shown in Fig. [31] and [32]to groove the steel bars for the NSM technique and also they experimented with the varying number of grooves.

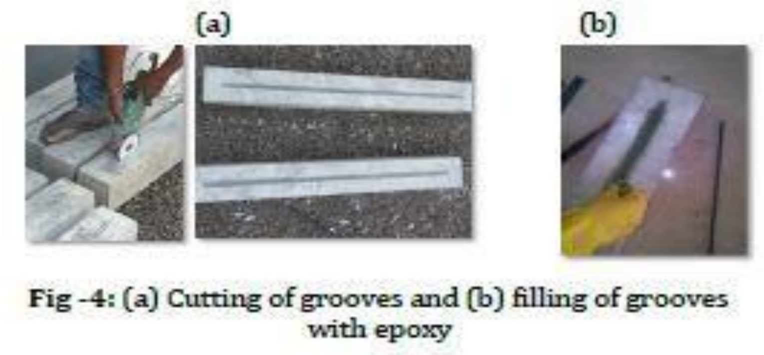


Fig:17 Experimental setups to groove the steel bars -NSM technique Ref(46)

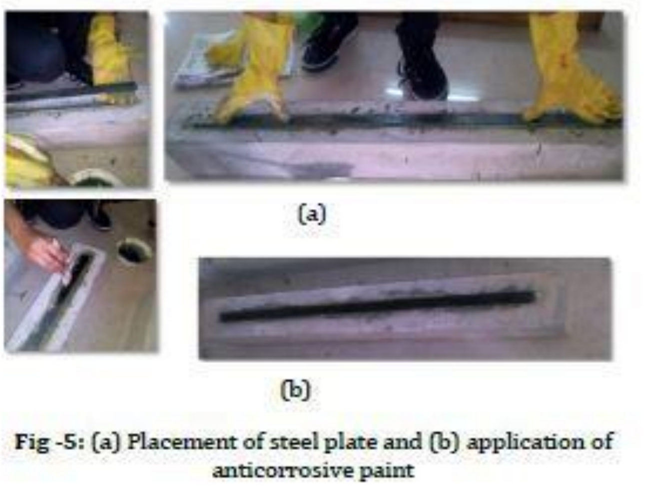


Figure 18 Experimental setup for the attachment of steel plate ref(46)

From the experimental test results, they made conclusions on different mechanical properties like load carrying capacity, the effect of ductility, and also on the effect of stiffness.The average increment of the ultimate load-carrying capacity was 82%, compared to that of the control beam.[46] They studied ductility in terms of two factors like deflection ductility and energy ductility. The deflection ductility of beams is calculated as the ratio of deflection at failure divided by the deflection at first steel yielding. Energy ductility of beams is calculated as the ratio of energy absorbed till failure divided by the energy absorbed till the first steel yielding.[46] As the tension reinforcement increased, the section changed from an under reinforced section to an over reinforced section. From the result, they observed lower ductility index values and also mentioned the change in failure mode was from ductile to brittle. They also concluded this combined method of strengthening was found to be effective for the beams with fewer mix ratios.

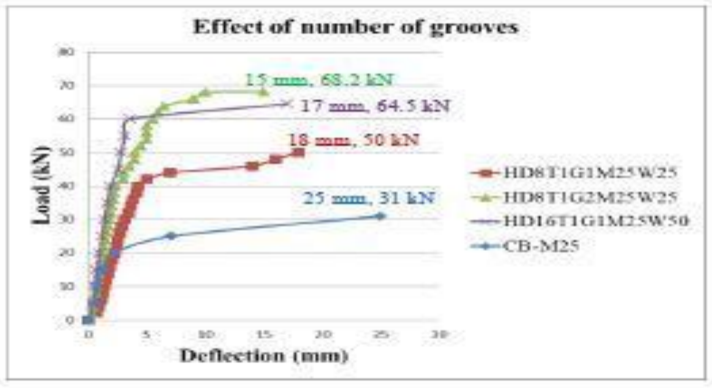
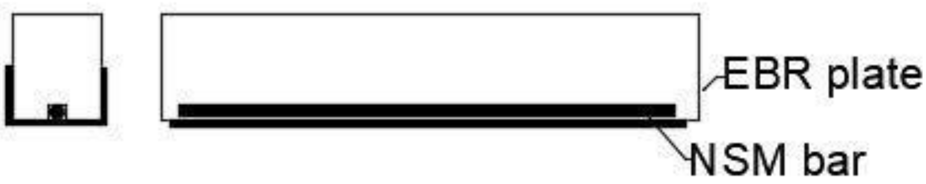


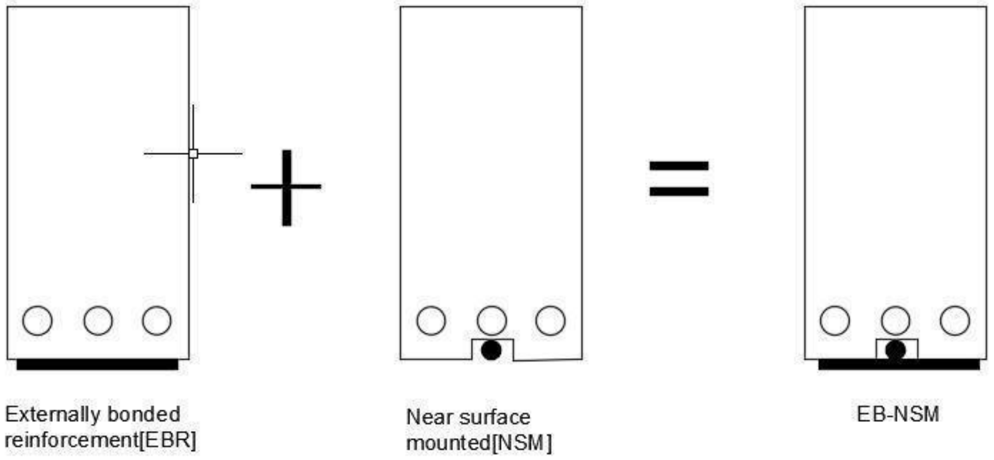
**Fig -16: Effect of Number of Grooves**

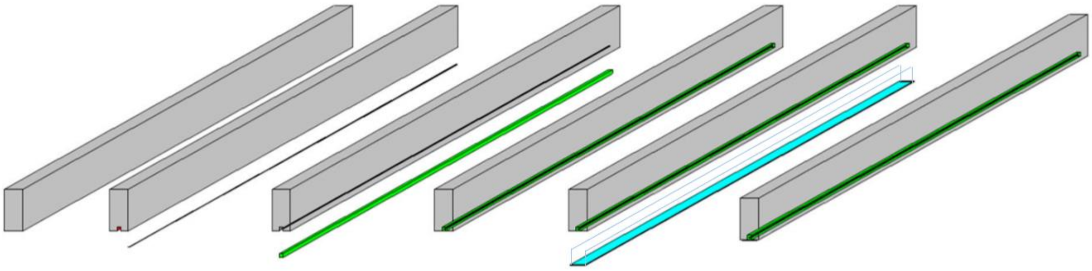
Fig: 19load-deflection curves with varying Number of grooves ref(46)

The above Fig. [33] explains the decrease in ductility values with an increase in several grooves which clearly explains that due to an increase in tensile reinforcement, the specimens were capable to take higher ultimate load compared to the single grooved bar.

To improve the ultimate load capacity and to enhance the ductile behavior of the beam, several merging techniques can be applied like the EB technique using U wrapping along with the FRP plate along the tensile face of the beam. The behavior of this application depends on the type of material used like carbon or glass. Based on a review from several papers and inspiration from their approaches in strengthening corroded beams. CFRP was a better material to improve the structural capacity of the corroded beam compared to GFRP. CFRP is an ideal material to be used to increase the structural capacity of a corroded beam. CFRP can exhibit 2 to 3 times gain in strength with proper FRP configuration on corroded beam i.e, wrapping technique or method incorporated in strengthening. N. Attari [48]experimented to determine the flexural strength of beam strengthening with CFRP and GFRP, made a statement that U-anchorage strengthening configuration improves the flexural strength and contributes to the redistribution of the internal forces through greater deformations of the specimens.Fig. belowshows the installation of fusion/hybrid technique to strengthen the corroded RC beam this technique was motivated to propose from the review work conducted on the strengthening of the beam with a combination of NSM and EBR technique,[46] the researchers carried out an experimental set up for the normal beams and strengthen to improve ductility and flexural strengthof the beam the results were surprising the strength of the repaired beam was higher than the normal beam in terms of taking the load and with large deflection making the beam ductile. The author concludedthe main intension behind this solution was to increase the bond area between the FRP interface and concrete to gain more strength. Based on this technique hybrid solution was proposed to gain higher flexural strength by using GFRP NSM bars in a pre sawn groovebinding it with epoxy upto surface level and wrapping with CFRP in this case we provide U laminate ti gain good anchorage to the beam thereby avoiding cover crushing and keep the RC beam as one unite to gain linear strain inthe concrete section.







*Picture gathered from : Darain, K., Jumaat, M., Shukri, A., Obaydullah, M., Huda, M., Hosen, M., & Hoque, N. (2016). Strengthening of RC Beams Using Externally Bonded Reinforcement Combined with Near-Surface Mounted Technique. Polymers, 8(7), 261. doi: 10.3390/polym8070261*

### 5.2.1 Improve structural load carrying capacity

Several kinds of research resulted in using carbon for the above merging technique increasing the flexural capacity of the beam and ductile behavior by providing glass. The technique is further improvised to avoid crack failure and to increase structural safety by wrapping the system. This system gives better confinement between concrete and the external FRP used. With references, reviews, and learning through limitations from different experimental tests, we combined a solution where CFRP bars can be grooved at the tension face of the beam with a sufficient amount of clear spacing between the bars. This strengthening method can be combined with externally bonded CFRP laminates in U shape. This combined solution is the structural method introduced to improve the ultimate load capacity of the beam by considering the material behavior of carbon.

In 2015, Belal Almassri et al. (6) worked on the behavior of corroded reinforced concrete beams strengthened with carbon fiber-reinforced polymer (CFRP) rods. They rehabilitated the structure using a near-surface mounted method (NSM) where rods were grooved along the tensile face of the beam.

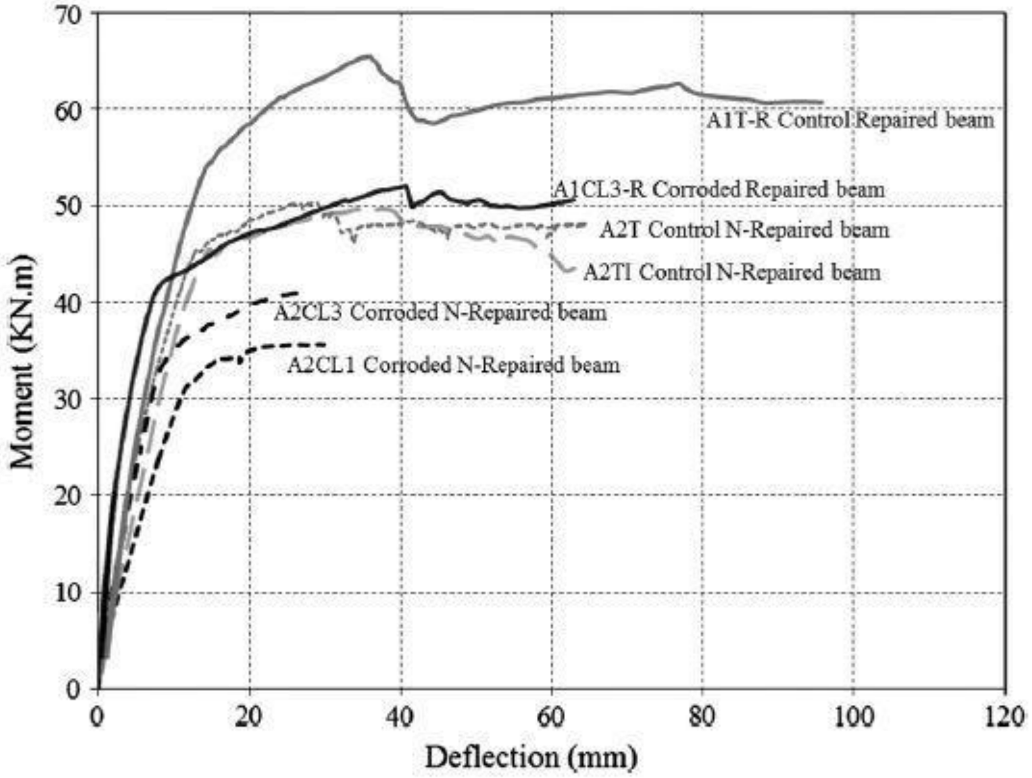


Fig: 20 Results plotted for an ultimate capacity of corroded, strengthened and controlled beams at different percentages of steel mass loss ref(6)

The above Fig. [34] explains the result of the ultimate capacity for corroded, strengthened, and controlled beams at different percentages of steel mass loss. The beam (A1CL3 -R) which had 38% maximum diameter loss in the tensile steel bars was corroded and repaired showed the maximum bending moment capacity compared to A2CL3 and A2CL1 which were corroded and unrepaired. The beam A1CL3-R had a failure due to concrete cover separation. Also from the results, authors concluded that every 1% loss of cross-section corresponds to 1% loss of yielding capacity, while there is more scatter in the case of the ultimate capacity as the failure mode varies for each beam.By studying through another important factor ductility, the above chart showed the ductile behavior of all the specimens used for the experiment. From the test results, authors specified that the ductility of corroded beams decreases 5 times for each 1% loss of cross-section but this could be unacceptable for the safety of a corroded structure. The NSM technique allows the initial ductility of the beam before corrosion to be recovered (6). In this paper, researchers found that an increase in ultimate load capacity could be possible with the NSM technique for the corroded repaired beam with the limitation to concrete cover separation. also, they mentioned The NSM technique restores sufficient ductility (2.8 times that of the non-repaired corroded beams) after ductility loss due to the brittle behavior of corroded RC beams because of steel corrosion. (6)

Another experimental test was conducted by Huifeng, Jin Wu, and Chengjun in 2019 where they used carbon fiber reinforced polymer in strengthening the corroded RC beams (19) that were subjected to different levels of corrosion. Here, authors, U wrapped the polymer throughout the beam as shown in the figure belowFig. [35]

Fig: 21 Experimental test for CFRP strengthened beam - ref(19)

From the test results, the authors concluded that the ultimate flexural capacity of the strengthened beams decreased due to an increase in the corrosion level.

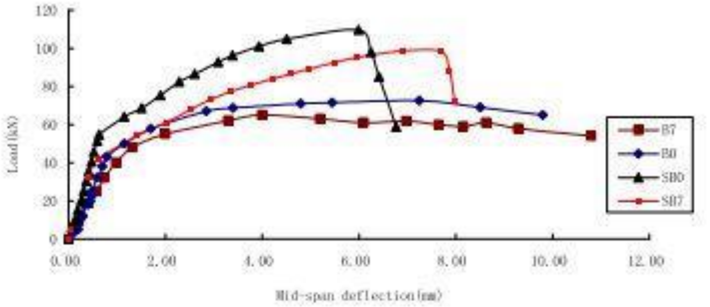


Fig: 22 Load -Deflection for a different level of corrosion ref(19)

From the above graph Fig. [36] plotted for the mid-span deflection, the authors concluded that the beam SB7 with the highest level of corrosion (13%) compared to other beams withlower levels of corrosion showed the maximum mid-deflection. After the yielding of tension reinforcements, the mid-span deflection increased significantly with increasing load.(19)

D.H.Lim in 2009 experimented with the effectiveness of flexural strengthening of concrete structures using a combination of NSM and EB CFRP strips (47). They also compared the result with the structures strengthened with only NSM CFRP strips. From the combined method of strengthening, they resulted in a 34.7% increase in ultimate strength when compared to a control beam and also with less deflection.

## 5.2.2 Restoration of ductility

The mechanical behavior of the beam can be improvised to be more ductile by following NSM and EBR techniques. From the review through several papers, researchers experimented on a few techniques like NSM and EBR in strengthening the corroded reinforced concrete beams some of them succeed to restore the ductility of the corroded beam. Almassri, Mahmoud, and Franchois in 2015 experimented with the behavior of corroded reinforced concrete beams repaired with NSM CFRP rods along with the comparison finite element study. near-surface mounted reinforcement (NSM) technique is one of the promising techniques used nowadays to strengthen reinforced concrete RC structures.(6). By studying the corrosion levels in the tensile steel bars and stirrups, they grooved CFRP rods along the tensile side and strengthened the corroded beams. They have shown that the NSM strengthened members can be expected to be much more ductile than externally-bonded-laminate (EBR) strengthened members and fail at much higher strain levels.(6) Almassri et al. (6) showed that the NSM technique also restored sufficient ductility despite the ductility loss of steel bars induced by corrosion. The NSM technique, which was used to repair corroded RC elements, restored significant ductility by avoiding premature failure of tensile bars at pit locations.(6). The mode of failure that occurred due to this technique was concrete cover separation as shown in Fig. [37] and the results were as expected when compared with ABAQUS and Finite modeling.

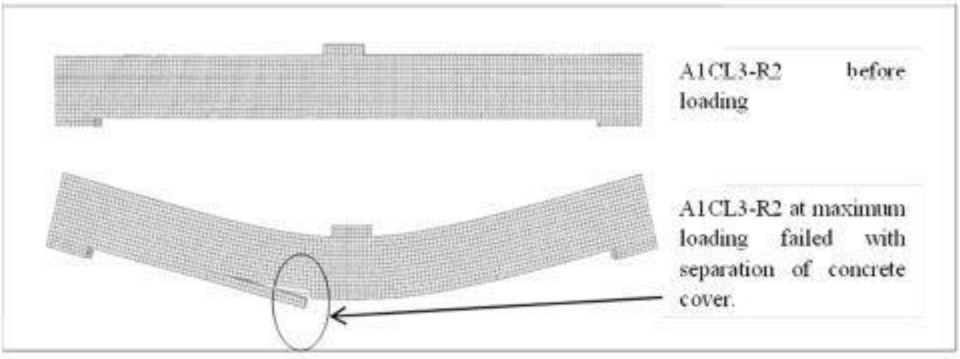


Fig: 23 Concrete cover separation-Mode of failure Ref(6)

Reinforcement corrosion in beam specimens has a marked reduction on stiffness and deflection of beams, flexural load capacity, and ductility. (38) To improve the mechanical behavior of the corroded beams M. Jamal and Suzan A investigated the replacement of corroded zones with different high-performance fiber-reinforced cementitious composites like GFRC (glass fiber reinforced), hooked steel fiber reinforced concrete (HSFRC), BCFRC (brass coated fiber reinforced), HBFRC (hooked brass fiber reinforced) and also PCC. From the experimental test results plotted for load-deflection under different levels of corrosion,the authors concluded that Beams cast with the GFRC cover zone showed the best performance compared to other beams. They had the following combination of properties: a good flexural performance especially under reinforcement corrosion; a good ductility; the least amount of strength reduction due to reinforcement corrosion.(38). The primary reason for that superior performance is that the intensity of glass fibers per unit volume is more than that of steel fibers. Below chartFig. [38] explains that even beams at a 5.5% degree of corrosion could exhibit high deflection at the ultimate load which had proved for good ductile performance.

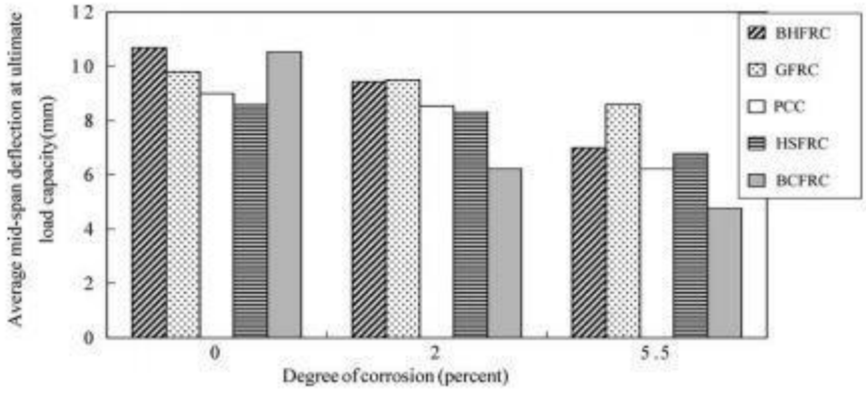


Fig: 24 Bar chart explaining the percentage of corrosion for different material at ultimate load capacity ref(38)

Professors Leema Rose, Suguna, and Ragunath in 2014 studied the behavior of corroded strengthened specimens using unidirectional cloth GFRP laminates (UDC). They aimed to improve both flexural capacity and ductility of the strengthened beams.

From the experimental test results, they concluded that The deflection at the yield load stage, UDCGFRP laminated beams exhibit a decrease of 17.28% at 10% mass loss and 83.78% at 25% mass loss, when compared to the corroded control beam. (40). UDCGFRP laminated beams show enhanced ductility. The increase in deflection ductility was found to be 62% at 10% mass loss and 58% at 25% mass loss. Professors also concluded that UDCGFRP laminated beams enhanced ductility behavior.

# 6

# CONCLUSION

## 6.1 General Conclusion

The aim and outcome thesis work has to deepen the knowledge of the effect of corrosion on the structural behavior of RC structures, to explore conventional retrofitting methods that have been practiced to strengthen the corroded structures and their evaluation of various materials used in terms of material properties and, literature review of strengthening methods using FRP adopted to strengthen the corrosion damage beam focusing on flexural capacity and restoration of ductility. In the initial part of the study, the effect of corrosion on structural behavior on RC structure was investigated by making a benchmark from the research papers and previous knowledge from courses. based on the outcome of this knowledge following conclusions were drawn and the purpose of this study was important for further work in the thesis:

- Understanding the effect of corrosion gave the gateway to learn how an RC structure can be strengthed to improve its structural behavior, corrosion occurs in two forms one, locally in some parts of the beam, and secondly, global corrosion which takes place throughout the beam. As a consequence of corrosion, it reduces the effective cross-section of structural components. This will reduce the axial, and flexural strength of elements, and makes them structurally weak.
- To know the type of strengthing technique, it is imported to know the formation of pitting stress acting on the corroded concrete leading to cracks with larger width making spalling of concrete cover and concrete crushing.
- Corrosion induces a weak bond between concrete and reinforcement there won't be any interaction between them this will result in inappropriate load transfer, which is a major factor to be known in strengthing to direct the force path.
- Corroded section elements will have lower ductility due to loss of steel property which means plastic deformation is restricted which intern affects seismic response and structural integrity.

After the study of the effect of corrosion and its response, the further idea was to familiarise with the conventional retrofitting solutions for corroded RC members using various materials and their purpose of strengthing mainly concerned with the increase in load-carrying capacity and ductility, the main conclusion of this analyses are as follows:

- The study of retrofitting solutions for the strengthening of corroded structure gave the idea of differentiating different materials in terms of characteristic properties for strengthening to determine which is ideal for its purpose, which is a vital element in strengthing any structural component.
- Exploring various strengthing solutions practiced in improving structural safety and serviceability gave knowledge of structural responses and their needs after strengthing In the case of bridges, the need for increasing their load carrying capacities requires the adoption of cost-effective machinery that will not interrupt the traffic considerably. In buildings, the reinforcement deterioration and changing needs for building occupancy imposes, in many cases, the strengthening of existing beams is prominent.

- This study gave the why FRP is an ideal material for strengthing corroded RC structures compared to other materials like steel or concrete in terms of strength, corrosion-resistant, cost, and ease of application in complex structures.

Using FRP reinforcement in rehabilitation is a highly practical strengthening system in the present world, its necessary to learn more bout strengthening solutions using FRP, review of research publications is done to subject the flexural strengthening of corroded RC structures and beams. The most significant conclusions of the review and comparisons are listed below:

- Significance of review of various strengthing solutions developed for corroded RC structure provides an overview concerned with the evaluation of the existing structure. To develop an appropriate strengthening scheme, an evaluation of the existing structure should first be conducted to determine the condition of the concrete, and its effect on structural performance. to know the load-carrying capacity of the structure to estimate the feasibility of using a particular strengthening method.
- The condition of the concrete surface highlights the necessity for the replacement of the cracked concrete parent material with a cementitious mortar of high strength before application of FRP reinforcement, the necessity of patch repair work depending on percent loss of steel reinforcement, to avoid the separation of the concrete cover and better structural performance.
- Corrosion level evaluation using the weight-loss method, Faraday's law, and average approximate value, gave an idea to determine the best suitable FRP strengthening solution for specific corrosion level.

With the knowledge from the chapters for the strengthening of corroded RC beams to identify the effective repair methods using FRP, composites play a vital role in improving structural load-bearing capacity and restore the ductility of corroded RC beams. the main conclusions drawn from the literature review are as the following:

- Study of the structural behavior of FRP strengthened beam is a key factor to improve the capacity of the corrosion damage RC structural elements, a lot of structures built a few years back needs to be maintained rather than replacing due to the present growing world the structural elements tends to take a larger load in coming years. therefore study on the repair of the corroded structural elements in load carrying capacity is prominent.
- Rather than brittle behavior exhibited by concrete, FRP confinement concrete tends to improve the ductility of the member which is an important study to be performed for the failure of the structural members due to corrosion damage to minimize the sudden collapse of the structure.

## 6.2 Scope for future research

The data available on naturally corroded reinforcement in concrete structures is less and it needs a lot of studies to be carried out on to know the various natural corrosions caused and their vast effects in all the structural details. Future large scale investigation and experiments have to be carried out on FRP repair on corrosion damaged concrete specimens which is more realistic for field conditions and the study of various failure modes and methods that are more appropriate for the problem.an advanced tool can be created by the industries to calibrate the loss of steel as a result of the loss what is the amount of strength loss is seen so that it would be appropriate for the stakeholders to choose the appropriate method for strengthing the RC structure to get better strength in service life.It would also be interesting to naturally corrode the RC members under real environmental conditions and then strengthen to get accurate structural behavior.Since the experiments are carried out in the laboratory therefore it is not sure that the RC members show the same behavior on site. Various aspects might change such as loading conditions such as dynamic loading and vibrations on the member, level of corrosion, and its initiation, so there will be a greater difference in the results. Further research has to be carried out to know as a result of corrosion whether sufficient flexural and shear capacity in the existing structure.

The specimens tested in the research papers were subjected to electrochemical corrosion as well as natural corrosion.But, there was no numerical analysis thatis carried out to find the force path after strengthing which would be a useful study that can be done to know the in-depth mechanism of bond stress between the components i.e, concrete, steel, and FRP. The present study works as a tool for further research work in the field of strengthening corroded RC members.

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