United Arab Emirates University
Scholarworks@UAEU

Theses

Electronic Theses and Dissertations

6-2004

Rehabilitation of concrete structure using composite materials

Ibtesam J.Saeed Al-saifi

Follow this and additional works at: https://scholarworks.uaeu.ac.ae/all_theses

Part of the Materials Science and Engineering Commons

Recommended Citation

Al-saifi, Ibtesam J.Saeed, "Rehabilitation of concrete structure using composite materials" (2004). *Theses*. 370.
https://scholarworks.uaeu.ac.ae/all_theses/370

This Thesis is brought to you for free and open access by the Electronic Theses and Dissertations at Scholarworks@UAEU. It has been accepted for inclusion in Theses by an authorized administrator of Scholarworks@UAEU. For more information, please contact fadl.musa@uaeu.ac.ae.

REHABILITATION OF CONCRETE STRUCTURE *USING COMPOSITE MATERIALS*

By

Ibtesam J. Saeed Al-saifi

Thesis submitted to

United Arab Emitters University

In partial fulfillment of the requirements

FOR THE DEGREE OF M. Sc. IN MATERIALS SCIENCE AND ENGINEERING

Supervisors:

Dr. Khalil Al-Hosani
Department of Civil Engineering
Faculty of Engineering
UAE University

Dr. Adel Hammami
Department of Mech. Engineering
Faculty of Engineering
UAE University

JUN, 2004

REHABILITATION OF CONCRETE STRUCTURE USING COMPOSITE MATERIALS

ABSTRACT

In the United Arab Emirates, most of the concrete structures including road, infrastructure and different types of buildings have been reported to be in need of rehabilitation. It is universally acknowledged that the environment of the countries in the Arabian Gulf is extremely severe and very aggressive to construction materials and operations. It is anticipated that the cost of rehabilitation of civil infrastructure will gradually increase over the next decade as a direct consequence of the increase in the number of structures reaching their expected service life.

Accordingly demand on rehabilitation methods will increase. In addition the severe climatic conditions of the country will require additional features for this method such as excellent exposure to high temperature fluctuation, moisture and UV contents. The main reasons of reinforced concrete structure's deterioration are corrosion of the steel bars (because of high temperature and humidity of the UAE environment) or continual upgrading of service loads (increase of the traffic load on bridges for example). The solution to these problems is to either re-build the structure or repair the concrete.

One of the promising solutions to this problem is to use fiber reinforced concrete (FRC) as replacement for the old methods of repair. The advantages of FRP are lightweight, high tensile strength, corrosion resistance, flexibility and electromagnetic resistance. The object cue of this thesis to, investigate the use of FRP as a strengthening method of concrete structures and its long-term performance, especially in the severe climatic conditions prevailing in the Arab Gulf region.

مكتبـــة الجيمـــي
JIMI LIBRAR

جامعة الإمارات العربية المتحدة
عمادة المكتبات الجامعية
UNIVERSITY LIBRARIES DEANSHIP
U.A.E. UNIVERSITY

UAEU Library
1000410403

ACKNOWLEDGEMENTS

In The Name Of God the Most Merciful the Most Compassionate

I would like to express my thanks and gratitude to Allah, the Most Beneficent, the Most Merciful whom granted me the ability and willing to start and complete this thesis. I pray to his greatness to inspire me the right path to his content and to enable me to continuo the work started in this thesis to the benefits of my country.

It is with my most sincerity that I express my gratitude to all of those who have supported me throughout my degree commitments. In particular I would like to thank my advisor Dr. Adel Hammami, who has both inspired and guided me throughout my thesis study. Thanks is also due to Dr. Khalil Al-Hosani who believed and showed interest upon my thesis and gave me the honor of being my main supervisor. I would also like to thank all labs' assistance Eng. Abdustar and Mr. Faisal who took care of my specimens and kept watch over them at times when I couldn't be present in person in the lab.

Special thanks to FOSROC, SIKA and IMI Alyosif's laboratory whom provided me with the necessary materials and required tests which I needed in my research and very grateful for there guidance and valuable notes along my study path. Last but not least, I would like to thank my family and my friends for there support and patience throughout my degree study journey.

TABLE OF CONTENT

LIST OF FIGURES

LIST OF TABLES

INTRODUCTION

1. Background

In a recent study, surveys of structures in the Arabian Gulf region have shown an alarming degree of deterioration within 10-15 years of construction. In this survey, 74% of the surface area observed in 42 concrete structures, showed at least some sever deterioration. Conventional repair methods are time consuming and offer limited protection to the structure [1]. In the case of reinforced concrete structures harsh environment is one of the main causes of concrete deterioration. The daily and annual temperature fluctuations are fairly high. The maximum temperature during summer reaches, approximately 70° C for structures exposed to the sun. The humidity in the region is also high because of the high temperature and rate of transpiration in the Arabian Gulf making the production of good and durable concrete difficult. Poor quality construction is susceptible to rapid deterioration even in projects where a higher quality has been achieved; there have been several instances where the concrete's long term structural performance has fallen well short of that expected elsewhere in less aggressive situation. Also one of the greatest deterioration of current infrastructure design is the failure to design for change of use, maintenance and replacement of parts during the full design life. Hence structures are needed, which can be rapidly rearranged, extended and strengthened. This suggests a modular approach with functions, which are separated instead of being integrated. The requirements of clients for future life in buildings, highways, bridges, airports, offshore structures, mass transit systems, water supply, water treatment and solid waste disposal has been examined in detail by the construction industry and a set of performance objectives establish. The success of advanced composites in penetration the large construction markets will be entirely dependent on their ability to meet these objectives. Development of successful designs requires a fundamental reappraisal of the appropriate combination of different materials to how the whole process of manufacture, design and construction can be improved to match the objectives as closely a possible. It is likely as a result that structural forms in all these applications will eventually change out of all recognition and will often consist of a combination of materials, all providing their unique benefits. Conventional repair methods are time consuming and offer limited protection to the structure. Fiber reinforced polymer (FRP) composites have been demonstrated to provide an economical solution to these repair and rehabilitation problems, FRP composites show promise for new construction as alternatives to traditional materials. These installations are on such structures as beams, columns, decks/slaps, walls, arch, and tunnels. Many of these repairs were mad to highway structures, buildings and even historical monuments.

2. Objectives

The focus of this study is to determine the behavior of fiber-reinforced polymer for possible use in rehabilitation of concrete structures. The FRP sheet materials will be bonded to the external face of non-reinforced concrete beam; criteria examined are the load-deflection response and cracking patterns under static load for repaired beam by FRP system. Furthermore the aim of this work is to update knowledge on the subject of durability and lifetime prediction of FRP as reinforcement for concrete by experiments and service life prediction. Experiments will be performed in a different manner, either simulating in lab oratory equipments (accelerating degradation) or on actual environment for long period of time.

In chapter 1, which is an introductory chapter that gives the reader the background to the topic and the reason for selecting this subject to be studied, by discussing the mechanisms of concrete's deterioration according to different conditions either by environment or by workman ship. Followed by, traditionally used methods of repairing concrete compared with this new system of repairing using, composite material (FRP).

Chapter 2 is aimed to provide the reader with general information and properties about concrete and FRP composites and their constituents regarding environmental resistance. This chapter concentrates on the mechanical properties of FRP and environmental effects such as temperature, humidity, alkalinity, influence of UV light and fire hazards due to its flammability. The mechanisms of damage of FRP-Concrete system are discussed according to environment effects at the end of chapter 2.

Chapter 3 presents design guidelines for concrete structure repaired using FRP reinforcement, starting with different functions of FRP on concrete structure and roles of application of the system. Design principles are very important issues in order to get full benefits of this system.

In chapter 4, experiments conducted on this project are described with the discussion of results. A special characterization section is dedicated to the analysis of the fractured surfaces of composite specimens using SEM. Conclusions and recommendations for future works are provided in chapter 5.

Chapter -1-

Chapter 1

Degradation of Reinforced Concrete Structures

1.1 INTRODUCTION

In general the environment of the Arabian Peninsula is aggressive, particularly to reinforced concrete structures. Many of the problems have been recognized but improvement in performance of new work, with dependable maintenance and repair will only result if there is a wider acceptance of the need for high standards. The application of design life concepts supported by life cycle costing can help to identify and show the benefits that will result from accepting the relatively higher levels of cost needed to ensure the necessary standards are achieved [2].

1.2 DETERIORATION MECHANISMS

Due to the nature of structural concrete, by resembling natural stone, this material was long considered an eternally lasting maintenance free building material. In the past this problem has been seriously revised, particularly for reinforced and pre-stressed structures exposed to aggressive chloride containing environments. Nevertheless the durability problems with concrete structures are few but the consequences of having prematurely deteriorating structures are very serious and costly. Chloride induced reinforcement corrosion is the main well known problem into Middle East and it is not yet under full control. Initially, through lack of knowledge chlorides were mixed into the concrete using chloride contaminated sand and water if not seawater and coarse aggregate. However the problems appeared this time because the quality of the concrete mix, the compaction and the curing is sufficient. In the highly chloride contaminated atmosphere of the Gulf's coastal regions, combined with high temperatures and often very high moisture levels, chlorides from the outside quickly accumulated on the concrete surface and penetrated into the outer layer and reached the reinforcing steel. Corrosion was initiated. Similarly the chloride and sulfate contaminated grounds of the coastal region, i.e. the sabkha, turned out to be some of the most aggressive soils for reinforced concrete **[3]**. The number of really significant deterioration mechanisms in the Gulf region is limited. There are actually only three basic mechanisms to consider:

1.2.1 Electro-chemical deterioration

Corrosion of steel reinforcement having been rusted either, by carbonation or chloride contamination of the surrounding concrete or a combination of both. Under very moist conditions, black rust with very limited expansion may occur, leading to steel cross section reduction without the valuable warnings of cracks and spalling **[3]**. The electro-chemical process driven by the cell leads to local corrosion of reinforcement, which can also lead to cracking, or spalling of the surrounding concrete **Figure (1-1)**. A rare, but potentially more dangerous, form of chloride-induced corrosion can result when strong electrical forces are developed without sufficient oxygen being present to enable the corrosion products to oxide. The resulting anaerobic corrosion products are not expansive and usually cause immediate damage to the surrounding concrete. In such cases the reinforcement can be reduced in cross-section due to pitting and in a very extreme case could be eaten away altogether. In many parts of the region particularly on the coast of the gulf the background presence of high levels of chloride makes chloride induced corrosion the most important durability issue. The basic lines of defense are however similar for both carbonation and chlorides involving the use and provision of high quality impermeable concrete of adequate thickness as cover to the reinforcement **[2]**.

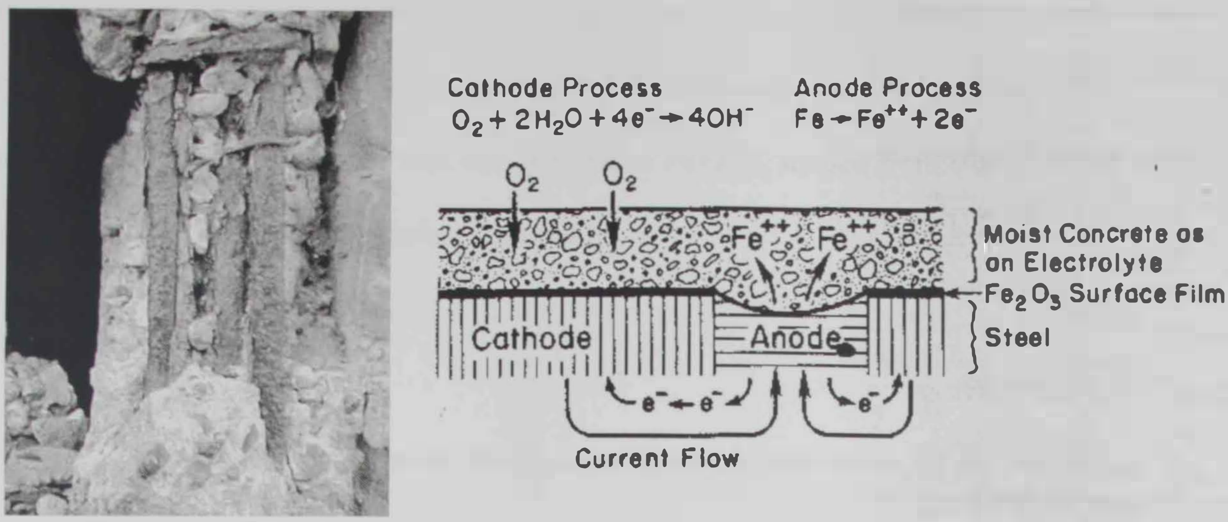


Figure (1-1): *The Electrochemical process of steel corrosion. (Mehta and Monteiro 1993).*

The following equations describe the electrochemical process involved in steel corrosion (Mehta 1991):

Anode Reaction: $Fe \rightarrow 2e^- + Fe^{2+}$

Cathode Reaction: $\frac{1}{2}O_2 + H_2O + 2e^- \rightarrow 2(OH)^-$

Adding Reactions: $Fe + \frac{1}{2}O_2 + H_2O \rightarrow Fe^{2+} + 2(OH)^- \rightarrow$ *iron oxide*

Carbonation occurs when carbon dioxide from the air penetrates the concrete and reacts with hydroxides, such as calcium hydroxide, to form carbonates. In the reaction with calcium hydroxide, calcium carbonate is formed:

$$Ca(OH)_2 + CO_2 \rightarrow CaCO_3 + H_2O$$

This reaction reduces the pH of the pore solution to as low as 8.5, at which level the passive film on the steel be not stable. Carbonation is generally a slow process. In high-quality concrete, it has been estimated that carbonation will proceed at a rate up to 1.0 mm (0.04 in.) per year. The amount of carbonation is significantly increased in concrete with a high water-to-cement ratio, low cement content, short curing period, low strength, and highly permeable or porous paste. Carbonation is highly dependent on the relative humidity of the concrete. The highest rates of carbonation occur when the relative humidity is maintained between 50% and 75%. Below 25% relative humidity, the degree of carbonation that takes place is considered insignificant. Above 75% relative humidity, moisture in the pores restricts CO_2 penetration. [4]. Carbonation-induced corrosion often occurs on areas of building facades that are exposed to rainfall, shaded from sunlight, and have low concrete cover over the reinforcing steel [5].

1.2.2 Chemical Deterioration

Concrete reacting with the surrounding media causing either expansions of the concrete leading cracking and spalling alkali-aggregate reactions **(AAR)**, sulphate attack or dissolution and disintegration of the cement past, which binds the fine and coarse aggregates [3].

In most concretes, aggregates are more or less chemically inert. However, some aggregates react with the alkali hydroxides in concrete causing expansion and cracking over a period of years. This *alkali aggregate reactivity* has two forms, *alkali-silica reaction* **(ASR)** and *alkali-carbonate reaction* **(ACR)**. ASR is of more concern than ACR because aggregates containing reactive silica materials are more common. Aggregate containing certain forms of silica will react with alkali hydroxide in concrete to form a gel that swell as it draws water from the surrounding cement paste or the environment. In absorbing water these gels can swell and induce enough expansive pressure to damage concrete, typical indictors of (ASR) are map (random pattern) cracking and in advanced cases closed joints and spalled concrete surfaces. Cracking usually appears in area with frequent supply of moisture such as close to water line in piers, from the ground behind retaining walls, near joints and free edges in pavements or in piers of columns subject to wick action. The deterioration caused by (ACR) is similar to that caused by (ASR) however, alkali-carbonate reaction is relatively rare because aggregates susceptible to this reaction are less common and are usually unsuitable for use in concrete for strength potential.

Sulfate attack naturally occurring sulfates of sodium. potassium, calcium or magnesium are sometimes found in soil or dissolved in ground water. Environmental conditions have a great influence on sulfate attack. The attack is greater in concrete exposed to wet/dry cycling. When water evaporates, sulfates can accumulate at the concrete surface, increasing in concentration and their potential for causing deterioration. Porous concrete is susceptible to weathering caused by salt crystallization. Examples of salt known to cause weathering of field concrete include sodium carbonate and sodium sulfate. Under drying conditions, salt solutions can rise to the surface by capillary action and as a result of surface evaporation, the solution phase becomes supersaturated and salt crystallization occurs, sometimes generating pressures large enough to cause cracking and scaling. Sulfate attack is a particular problem in arid areas, seawater also contains sulfates but is not as severe and exposure to sulfates in ground waters [5].

1.2.3 Physical Deterioration

Abrasion and wear, or salt scaling due to re-crystallization of salt in the pores where the expansive pressure of crystal growth lead to surface scaling of concrete of poor or mediocre quality ands strength [3].

Seawater may be encountered with a range of concentrations of dissolved salts, though always with a constant proportion of the constituents to one another. The concentration is lower in the colder and temperate regions than in the warm seas, and especially high in shallow coastal areas with excessive diurnal evaporation rates. Where concrete structures are placed on reclaimed coastal areas with the foundations below the saline ground water levels, capillary suction and evaporation may cause super saturation and crystallization in the concrete above ground, resulting both in chemical attack on the cement paste (sulfate), and in aggravated corrosion of steel (chlorides). In tropical climates these combined deleterious effects may cause severe defects in concrete in the course of a very few years. The reaction of mature concrete with the sulfate ion in seawater is similar to that with sulfate ion in fresh water or leached from soils, but the effects are different. The concentration of sulfate ion in seawater can be increased to high levels by capillary action and evaporation under extreme climatic condition [4].

Abrasion damage occurs when the surface of concrete is unable to resist wear caused by rubbing and friction. As the outer paste of concrete wears the fine and coarse aggregate are exposed and abrasion and impact will cause additional degradation that is related to aggregate to past bond strength and hardness of the aggregate. Although wind bone particles can cause abrasion of concrete, the two most damaging forms of abrasion occur on vehicular traffic surfaces and in hydraulic structures such as spillways and tunnels [5].

The durability of reinforced concrete and the factors involved in all aspects of maintenance and repair are currently of concern in many parts of the world. These matters are of particular importance in the Arabian Peninsula because of the difficulties encountered in the use of reinforced concrete in the hot, arid and often salt laden environment particularly that of the Gulf coast. In such conditions, poor quality concrete deteriorates rapidly, and even when high standards are set in design and specification requirements, unless these can be matched by high standards of construction work, there are many indications that performance will not measure up that expected in the temperate climates of parts of North America or Western Europe. There are several other areas of the world where the climate is hot and dry, and recommendations of hot weather concreting have been developed. But in the Arabian Peninsula a direct and successful application of such recommendations is not always possible, as the situation is made worse by a combination of adverse environmental factors.

The climate is hot and arid. Evaporation greatly exceeds precipitation. Because of the semi enclosed nature of the Gulf, constricted as it is at the Straits of Hormuz, and with only a relatively small range of tidal movement, there is little tendency for the interchange of water between the Gulf, the Gulf of Oman and the adjoining Arabian Sea. In this situation, water is extracted from the Gulf by evaporation leaving a residue of salts, which have built up, to very high levels. The amount of chloride and sulfate can, particularly in the shallow coastal areas be 20% or greater than that in the open sea. A similar set of circumstances apply to the Red Sea where salt levels are about 10% higher than in open sea situations. While conditions in the Gulf of Oman, the Arabian Sea, and the Gulf of Aden are not as severe there are still high levels of salinity combined with high, or relatively high water temperatures.

Because of its geographical location within the high-pressure zone of the Tropic of Cancer the level of solar radiation is very high throughout the Arabian Peninsula as the sky is seldom overcast. This means that materials exposed to direct sunlight develop very high temperatures, thermal movements and the effects of restraints are large, and chemical reactions such as the hydration of cement or chemical attack are extremely rapid.

With the development of high temperatures during the day, and the sometimes-rapid fall of temperature at night, local temperature ranges can be relatively large. This in turn places an additional burden on structures, as the resulting range of thermal movement can also be quite large. Temperature changes are accompanied by major changes in relative humidity, which are also affected by the direction of the wind and proximity of the sea.

For Arabian Peninsula both during summer and winter the relative humidity may range from as low as 5% to as high as 90% or more. The average relative humidity is about 50% in the summer and 70% in the winter [2].

1.3 TARGETED ASSESSMENT FOR SELECTIVE REPAIRS

For assessment, maintenance and repair planning two decision situations can be distinguished for practical reasons, namely design of repair new structures and maintenance and repair of existing structures.

For existing structures the optimal inspection, repair and strengthening actions may be identified, based on evaluations of their influence on the immediate repair or strengthening costs, the expected failure costs and the expected future maintenance costs. Structural maintenance planning usually involves one or more assessment analyses and actions followed by decisions on re-qualification, rehabilitation and sometime even replacement of the structure. Due to the close interrelation between the use of the structure, the actual and the future state and safety of the structure, decisions regarding re-qualification and rehabilitation can't be carried out if a strategy for the future maintenance of the structure has not been decided upon.

Assessment may be seen as an adaptive process of defining the state of knowledge about the present and the future state of the structure. Typically, a structural assessment may thus involve a review of project documentation, inspection, testing of materials, testing and monitoring of the structure performance, refined numerical analysis and planning of future inspections. Refinements adaptability of the state of knowledge or necessity of collecting further information is always based on all the actually achieved knowledge and the expected life cycle cost reductions, including expected malignance and failure costs information. If a repair procedure and repair material is not selected from a clear understanding of how the repair is intended to influence the deterioration mechanism favorable with respect to durability, the chances of obtaining a successful repair are small. The only way to control a deterioration process is by controlling the parameters governing the mechanism. The assessment of structures targeted towards a few realistic repair methods, using selective methods can diminish the usually very high costs for inspection and testing of structures followed often by expensive repair methods using exorbitantly expensive proprietary repair materials. Although these materials have valuable merits, they are being marketed very effectively maybe more than there documented performance my warrant. It should be remembered that good quality concrete is often the best repair material for damaged concrete structure; it has deformation characteristics and moisture transport characteristics compatible with the parent concrete. That is in itself a valuable asset not possessed by the majority of proprietary repair materials, especially polymeric based materials. For very deteriorated structures the decision of non-repair will often be the most economic, and in some cases careful monitoring and regular inspections may keep such structure in safe operation for several years, without any or only limited repairs, leaving time to plan a replacement structure. Inspection and assessment based mainly on visual inspections my hide the oncoming serious deterioration, thus delaying the possibility to interfere before serious damage has occurred. This is a serious drawback of visual inspections and some intelligent testing based on details knowledge of the environment and the mechanisms of deterioration is essential if low-cost optimal life prolonging measures shall be used [3].

1.4 CONVENTIONAL METHODS OF REPAIRING CONCRETE

When the results of an investigation have been evaluated, those making decisions on the future of a structure have various options. These range from doing nothing (if the structure is only required for a few more years and can continue to be operated safely), to complete demolition and replacement. Clearly, there can be huge financial implications for the owner who needs to be represented and involved in discussions on the way forward the suitable methods financially and technically [6]. Following some of repairing methods:

1.4.1 Reinstatement with Concrete or Mortar

1.4.1.1 The *Dry-Pack Method*

The dry-pack method can be used on small holes in new concrete, which has a depth equal to or greater that, the surface diameter. Preparation of a dry-pack mix typically consists of about 1 part Portland cement and 2 1/2 parts sand to be mixed with water. Dry pack method consists of ramming a very stiff mixture into place in thin layers. It is suitable for filling form tie-rod holes and narrow slots, and for repairing any cavity, which has a relatively high ratio of depth to area. Practically no shrinkage will occur with very stiff mixtures, and they develop strength equaling or exceeding that of the parent surfaces of the concrete, which must be thoroughly cleaned, preferably by wet sandblasting. Special measures must be taken where chlorides are a factor in the deterioration; you then add enough water to produce a mortar that will stick together **[4, 6]**.

1.4.1.2 *Concrete Replacement*

Concrete replacement is the desired method if there is honeycomb in new construction or deterioration of existing concrete, which goes entirely through the wall or beyond the reinforcement, or if the quantity is large. For new work, the repairs should be made immediately after stripping the forms. Considerable concrete removal is always required for this type of repair. Excavation of affected areas should continue until there is no question that sounds concrete has been reached. Additional chipping may be necessary to accommodate the repair method selected and shape the cavity properly. Concrete for the repair should generally be similar to the old concrete in nominal maximum size of aggregate and water-cement ratio, provided durability is not sacrificed. Color is important in some exposed concrete. Forming will usually be required for large repairs in vertical surface. **[4]**

1.4.1.3 *Replaced-Aggregate Concrete*

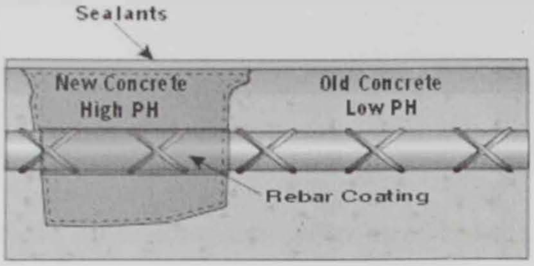
Replaced aggregate concrete may be used advantageously for certain types of repairs. It bonds well to concrete and has low drying shrinkage. It is also well adapted to under water repairs. This is a specialized process, which is described in ACI 304R. **[4, 6]**

1.4.1.4 *Shotcrete (Gunite)*

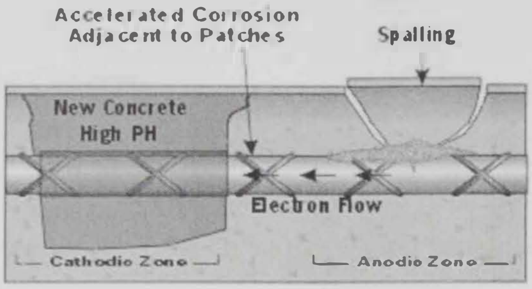
A popular concrete replacement technique for repairing large areas of severely deteriorated concrete and spelled vertical and overhead faces is the use of pneumatically placed concrete or shotcrete. Properly applied shotcrete has excellent bond with new or old concrete and is frequently the most satisfactory and economical method of making shallow repairs. It is particularly adapted to vertical or overhead surfaces where it is capable of supporting itself without a form, without sagging or sloughing. Shotcrete repairs generally perform satisfactorily where a recommended procedure of ACI 506R are followed, Simplified equipment has been developed for use in small repairs. Shotcrete consists of a mixture of moistened cement and fine aggregate (sand) that is sprayed onto the repair area under pressure. **[4, 6]**

1.4.1.5 *Repair of Scaled Areas and Spalls in Slabs*

Scaling of concrete pavement surfaces is not unusual where they are subject to deicing salts, particularly if the concrete is not adequately air-entrained. Such areas may be satisfactorily repaired by a thin concrete overlay provided the surface of the old concrete is sound, durable, and clean. A minimum overlay thickness of about 1 1/2-in. (38 mm) is needed for good performance (ACI 316R). The temperature of the underlying slab should be as close as possible to that of the new concrete. Spalls may occur adjacent to pavement joints or cracks. Spalls usually are several inches in depth, and even deeper excavation may be required to remove all concrete, which has undergone some slight degree of deterioration. They may be repaired by methods similar to those used for scaled areas. Numerous quick-setting patching materials, some which are proprietary, are available **[4]**.



Conventional Repair



Secondary Spalling

Figure (1-2): *Repairing corrosion spalled area using traditional methods.*

Once contaminated, the corrosion will continue and repairs may be needed every 3-5 years unless corrosion is effectively stopped. Traditional methods of repairing the spalled areas, chasing corrosion, treating exposed rebar, and/or waterproofing the concrete may not stop corrosion from propagating. In fact these procedures could accelerate the corrosion process.

1.4.1.6 *Mortar Repairs*

Mortar is generally used for relatively small repairs (typically less than 1 m^2) that are placed by hand. The mortars themselves are usually proprietary products containing sand, cement, polymer, other minor constituents and in some cases fibers. The polymers may be in powder form, combined with the other materials or in liquid form in which case they are supplied in separate container. The polymer component has three separate functions. Firstly, it acts as a plasticizer and reduces the amount of water required to produce a workable mix. Secondly, it decreases the permeability of the hardened mortar to chlorides in solution and to carbon dioxide. Thirdly, it improves the bond with the substrate.

1.4.1.7 *Spray Concrete*

Two processes, wet and dry, produce sprayed concrete. In both processes, mortar or concretes conveyed through a hose and projected pneumatically at high velocity from a nozzle into repair. No other compactions required but the surface is finished by hand if this is required.

1.4.2 Coatings for Concrete

Coatings are used both in the repair process and also to protect new structures, there are many different types of coating, in term of their chemistry, but they can be grouped into three categories base on their mode of action:

Barrier coatings:

Form a physical film on the concrete surface typically 300 μm to 1mm thick. Materials used in this way include epoxies, acrylics, polyurethane, polyesters and polymer cement coating. Each has different properties and applications.

Pore blockers:

Do not form a film on the surface. They are liquids of low viscosity based on solvents. When applied to concrete surfaces, they are able to penetrate the minute capillary pores to a certain degree. Once absorbed into the surface, they solidify by solvent evaporation, crystallization or polymerization.

Pore liners:

Are base on silanex or siloxanes. They may consist of the almost pure a compound or be solvent. Silanes and siloxanes, also penetrate the concrete surface with out forming a surface film. They react with the silica present in the paste to produce hydrophobic (waterrepelling) compounds that are chemically bound to the hydration products. The hydrophobic compounds cover the surface and line the pores to depth to which are able to penetrate [6].

1.4.3 Crack Injection

Cracks need to be treated only when they are a potential threat to the durability of the reinforcement or are causing unacceptable leaks. Polymers used in injection of cracks include epoxies, acrylics, polyesters and polyurethane. Each has different properties and is used for different circumstances. Resin is injected under pressure either into inlet ports that have been stuck to the concrete surface over the crack or through holes drilled to intersect the crack. Resin injections are a skilled process and should only be undertaken by specialists [6].

1.4.4 Corrosion Inhibitors

Corrosion inhibitors fall into two general types: corrosion-inhibition admixtures used in a concrete mix during construction and migrating corrosion inhibitors that can be used for existing concretes. In repair work consideration should be given to the use of migrating inhibitors, but opportunities for their use are confined to large areas of repair where the likelihood of establishing zones of variable electrical properties is remote [6].

1.4.5 Cathodic Protection

In a reinforced concrete structure, the metal to be protected by the impressed current -the reinforcement- is distributed close to the surface of the concrete but encapsulated in it. Concrete is a relatively poor conductor of electricity. These two factors mean that in order to provide adequate protection, in most cases the anode has to be distributed over the surface. The alternative approach is to use many discrete anodes at regular intervals in drilled holes in the concrete [6].

1.4.6 Re-Alkalization

The objective of re-alkalizations is restoring the alkalinity in carbonated concrete and to re-establish a passive environment around the reinforcement with the minimum of disruptions to the concrete. The system involves passing and electrical current through the concrete to the reinforcement using an externally applied anode that is attached to the concrete's surface. During this process re-alkalization is achieved as an alkaline electrolyte, generally a sodium carbonate solution, is taken into the concrete. At the same time, electrolysis ate the reinforcement surface produces a high pH environment. This restores the passive alkaline environment and protects the steel from corrosion [6].

1.4.7 Chloride Extraction (Desalination)

Chloride extraction achieved by applying an electrical field between the reinforcement and an externally mounted anode mesh. During the process chloride ions are transported towards the anode and out of the concrete. At the same time electrolysis at the reinforcement surface produces a high pH environment. This re-establishes a passive environment around the reinforcement [6].

1.5 ADVANCED METHODS OF REPAIRING CONCRETE

The strengthening and repairing of concrete structures with externally bonded reinforcement, generally done by using either steel plates or FRP laminates. Each material has its specific advantages and disadvantages. Steel plates have been used for many years due to their simplicity in handling and applying and to their effectiveness for strengthening. The properties and behavior of steel-concrete structures are well known. Steel plates are very effective to be used as bending reinforcement. The high tensile strength and stiffness lead to an increase in bending capacity and a reduction of the deformations. Steel plates can also be used as external shear reinforcement. However, labor costs might rise quickly. Steel stirrups have to be bending or welded and very needed, these costs‚can make this technique economically less interesting.

FRP sheets have very high tensile strength and stiffness. Nevertheless, they cannot be used in every strengthening situation. When used in bending, the active stresses in the FRP laminates have to be kept small in order to prevent the internal steel reinforcement from yielding. This means that the high strength properties of the FRP sheets are not used effectively. The required increase of bearing capacity can only be reached by adding a considerable number of sheets, which increase the material and labor costs. For limiting the deflections, FRP sheets are not very effective. Due to their very small cross sectional area per sheet, the moment of inertia will only slightly increase and so the deformation decrease will only be marginal. In these cases, very often-steel plate offers a better alternative. On the other hand, FRP sheets are more appropriate for shear strengthening than steel plates. An orthogonal net of fibers bonded at both sides of a beam is very well able to take shear forces. The applying of the FRP sheets is very easy. Even complex shapes and geometries can be done. Labor costs are considerably lower for FRP than for externally bonded steel stirrups [7].

It should be clear that on real construction and maintenance process, contractor couldn't stop using any of above methods, conventional methods or advances methods regarding circumstances. Life cycle coasting assessments can also help in the planning of maintenance and repair work, it is often necessary in consider in such operations to carefully plan a programmed in which the difference in performance and cost between patching and complete repair is understood. It may not be economical to carry out a full-scale operation unless the causes for the deterioration are well identified and can be dealt with at the same time.

So, several policies are available for repair programming, ranging from the short-tem temporary repair to the undertaking of a full-scale renewal. The choice of action depends on a number of factors including:

1. *The cause and rate of deterioration*
2. *The cost of different types of repair*
3. *The disruption and disturbance to the building occupants and time required for repair*
4. *The relationship between the physical life and their repair, and required physical, functional and economical life of the building.* **[2]**

Chapter -2-

Chapter 2

Fiber Reinforced Polymer Composite Properties

2.1 INTRODUCTION

Many fibers reinforced composite materials offer a combination of strength and modulus that are either comparable to or better than many traditional metallic materials. Because of their low specific gravities, the strength-weight ratios and modulus-weight ratios of these composite materials are markedly superior to those of metallic materials. In addition, fatigue strength-weight ratios as well as fatigue damage tolerances of many composite laminates are excellent. For these reasons, fiber-reinforced composites have emerged as a major class of structural material and are either used or being considered as substitutions for metals in many weight-critical components in aerospace, automotive and other industries where is the coast neglected to the function.

Traditional structural materials, such as steel and aluminum alloys, are considered isotropic since they exhibit nearly equal properties irrespective of the direction of measurement. In general, the properties of fiber-reinforced laminate are the maximum when these properties are measured in the longitudinal direction of fibers. At any other angle of measurement, these properties are lower. Particular in transverse direction the minimum value is observed at 90° to the longitudinal direction. Similar angular dependence so observed for other physical and mechanical properties, such as coefficient of thermal expansion, thermal conductivity and impact strength. Bi-or multidirectional reinforcement, either in the planar form or in the laminated construction, yields a more balanced set of property.

The design of a FRP structure is considerably more difficult than that of a metal structure see **Figure (2-1)**, principally due to the difference in its properties in different directions. However, an isotropic nature of FRP composite material creates a unique opportunity of tailoring its properties according to the design requirements. This design flexibility can be utilized to selectively reinforce a structure in the directions of major stresses, increase its stiffness in preferred direction, fabricate curve panels without any secondary forming operation, or produce structures with zero coefficients of thermal expansion. Another unique characteristic of many fiber-reinforced composites is their high internal damping. This leads to better vibration energy absorption within the material and results in reduced transmission of noise and vibrations to neighboring structures.

An advantage attributed to fiber-reinforced composites is their no corroding behavior. However, many polymeric matrix composites are capable of absorbing moisture diffusion by appropriate paints or coatings. Among the other environmental factors then may cause degradation the mechanical properties of some polymeric matrix composites are elevated temperatures, corrosive fluids, and ultraviolet rays **[8]**.

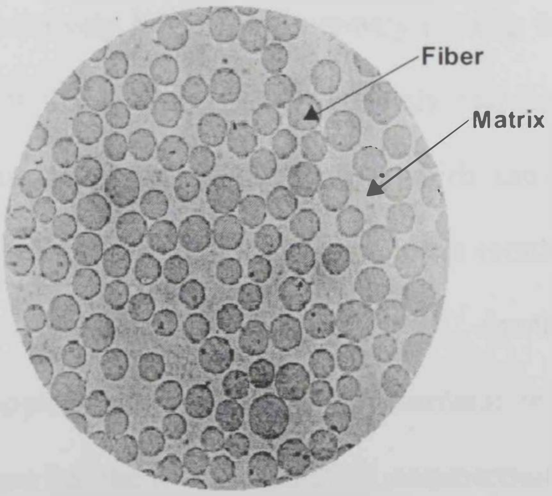


Figure (2-1): *Photomicrograph of a composite material*
(Journal of Composite Materials, 1997, Vol. 31, No. 1)

2.2 COMPOSITE CONSTITUENT

2.2.1 Fiber Reinforcements

The fiber is an important constituent in composites. A great deal of research and development has been done with the fibers on the effects in the types, volume fraction, architecture and orientations. The fiber generally occupies 30% - 70% of the matrix volume in the composites. The fibers can be chopped, woven, stitched, and or braided. They are usually treated with sizing such as starch, gelatin, oil or wax to improve the bond as well as binders to improve the handling. The most common types of fibers used in advanced composite of structural applications are glass, aramid and carbon. The glass is the least expensive and carbon being the most expensive. The cost of aramid fibers is about the same as the lower grades of the carbon fiber [9].

Glass Fibers

Glass fibers are the most common of all reinforcing fibers for polymeric (plastic) matrix composites (PMC). The principal advantages of glass fibers are low cost, high tensile strength, high chemical resistance and excellent insulating properties. The disadvantages are low tensile modulus, relatively high specific gravity (among the commercial fibers), and sensitivity to abrasion with handling (which frequently decreases its tensile strength), relatively low fatigue resistance, and high hardness (which causes excessive wear on molding dies and cutting tools). The two types of glass fibers commonly used in the fiber-reinforced plastics (FRP) industry are E-glass and S-glass. Another type, known as C-glass, is used in chemical applications requiring greater corrosion resistance to acids than is provided by E-glass. E-glass has the lowest cost of all commercially available reinforcing fibers, which is the reason for its widespread use in the FRP industry. S-glass, originally developed for aircraft components and missile casings, has the highest tensile strength among all fibers in use. However, the compositional difference and higher manufacturing cost make it more expensive than E-glass.

As in common soda-lime glass (window and container glasses), the principal ingredient in all glass fibers is silica (SiO_2). Unlike soda-lime glass, the Na_2O and K_2O content in E- and S-glass fibers is quite low, which gives them a better corrosion resistance to water as well as higher surface resistively. The internal structure of glass fibers is three-dimensional, long network of silicon, oxygen, and other atoms arranged in a random fashion. Thus, glass fibers are amorphous (non-crystalline) and isotropic (equal properties in all directions). The average tensile strength of freshly drawn glass fibers may exceed 3.45. However, surface damage (flaws) produced by abrasion, either by rubbing against each other or by contact with the processing equipment, tends to reduce it to values that are in the range of 1.72-2.07 GPa. Strength degradation is increased as the surface flaws grow under cyclic loads, which is one of the major disadvantages of using glass fibers in fatigue applications. Surface compressive stresses obtained by alkali ion exchange or elimination of surface flaws by chemical etching may reduce the problem; however, commercial glass fibers are not available with any such surface modifications. The tensile strength of glass fibers is also reduced in the presence of water or under sustained loads (static fatigue). Water bleaches out the alkalis from the surface and deepens the surface flaws already present in fibers. Under sustained loads, the growth of surface flaws is accelerated owing to stress corrosion by atmospheric moisture. As a result, the tensile strength of glass fibers is decreased with increasing time of load duration [8].

Carbon Fibers (Graphite Fibers)

Carbon fibers are commercially available with a variety of tensile module ranging from 207 GPa ($30x10^6$ psi) on the low side to 1035 GPa (150×10^6 psi) on the high side. In general, the low-modulus fibers have lower specific gravities, lower cost, higher tensile and compressive strengths, and higher tensile strains-to-failure comparing to the high-modulus fibers. Among the advantages of carbon fibers are their exceptionally high tensile strength-weight ratios as well as tensile modulus-weight ratios, very low coefficient of linear thermal expansion (which provides dimensional stability in such applications as space antennas) and high fatigue strengths. The disadvantages are their low impact resistance and high electrical conductivity, which may cause “shorting” in unprotected electrical machinery. Their high cost has so far excluded them from widespread commercial applications. They are used mostly in the aerospace industry, where weight savings is considered more critical than cost. Structurally, carbon fibers contain blends of amorphous carbon and graphitic carbon. The physical properties of carbon fibers such as electrical and thermal conductivities longitudinal coefficient of thermal expansion and oxidation resistance can be improved by controlling the amount of crystalline and eliminating the defects, such as missing carbon atoms or catalyst impurities. Tensile strength and tensile modulus are also affected by the amount of crystalline and the presence of defects. Carbon fibers are commercially available in three basic forms, namely, long and continuous tow, chopped (6-50 mm long), and milled (30-300 μm long). The long and continuous tow, which is simply a bundle of 1000 to 160,000 parallel filaments, is used for high-performance applications. The price of carbon fiber decreases with increasing filament count. Although high filament counts are desirable for improving productivity in continuous molding operations, such as filament winding and pultrusion, it becomes increasingly difficult to wet them with the matrix. “Dry” filaments are not conducive to good mechanical properties. Hybrid fabrics containing commingled or co weaved carbon and other fibers, such as E-glass, Kevlar, PEEK, PPS, etc. are also available. Techniques of forming three-dimensional (3-D) weaves with fibers running in the thickness direction have also been developed [8].

Kevlar 49 Fibers

Kevlar 49 belongs to a group of highly crystalline aramid (aromatic polyamide) fibers that have the lowest specific gravity and the highest tensile strength-to-weight ratio among the current reinforcing fibers. As a reinforcement, they are being used in many marine and aerospace applications where light weight, high tensile strength, and resistance to impact damage (e.g., caused by accidentally dropping hand tool) are important. Like carbon fibers, they also have a negative coefficient of thermal expansion in the longitudinal direction, which is utilized in designing low thermal expansion composite printed circuit boards. The major disadvantages of aramid fiber-reinforced composites are their low compressive strengths and difficulty in cutting or machining.

Although the tensile stress-strain behavior of Kelvar 49 is linear, longitudinal fragmentation, splintering, and even localized drawing usually precede fiber fracture. In bending, Kevlar 49 fibers exhibit a high degree of yielding on the compression side. Such a non-catastrophic failure mode is not observed in glass or carbon fibers, and gives Kevlar 49 composites superior damage tolerance against impact or other dynamic loading.

One interesting application of this characteristic of Kevlar 49 fibers is found in soft lightweight body armors and helmets used for protecting police officers and military personnel. Kevlar 49 fibers do not melt or support combustion but will start to carbonize at about 427°C. The maximum long-term use temperature recommended for Kevlar 49 is 160°C. They have very low thermal conductivity, but a very high vibration-damping coefficient. Except for a few strong acids and alkalis, their chemical resistance is good. However, they are quite sensitive to ultraviolet lights. Prolonged direct exposure to sunlight causes discoloration and significant loss in tensile strength. The problem is less pronounced in composite laminates in which the fibers are covered with a matrix.

Ultraviolet light-absorbing fillers can be added to the matrix to further reduce the problem. Kevlar 49 fibers are hygroscopic and can absorb up to 6% moisture at 100% relative humidity and 23°C.

The equilibrium moisture content is directly proportional to the relative humidity and is attained in 16-36 h. Absorbed moisture seems to have very little effect on the tensile properties of Kevlar 49 fibers. However, at high moisture content, they tend to crack internally at the preexisting micro voids and produce longitudinal splitting **[8]**.

2.2.2 Resin Systems

Resin is another important constituent in composites; there are two classes of resins consisting of thermoplastics and thermosets. A thermoplastic is solid at room temperature, which melted when heated and re-solidified when cooled. The long-chain polymers do not chemically cross-link. Because they do not cure permanently, they are undesirable for structural application. Conversely, a thermosetting resin will cure permanently by irreversible cross-linking at elevated temperatures. This characteristic makes the thermoset resin composites very desirable for structural applications. The most common resins used in composites are the unsaturated polyesters, epoxies, and vinyl esters; the least common ones are the polyurethane and phenolics, see **Table (2-1)** illustrate characteristics and limitations of the thermosetting resins **[9]**.

2.2.3 Fillers

Since resins are very expensive, it will not be cost effective to fill up the voids in composite matrix purely with resins. Fillers are added to the resin matrix for controlling material cost, improving its mechanical and chemical properties. Some composites that are rich in resins can be subject to high shrinkage, creep and low tensile strength, although these properties may be undesirable for structural applications [9]. The most common filler of polyester and vinyl ester resins is calcium carbonate ($CaCa_3$), which is used to reduce cost as well as mold shrinkage. Examples of other fillers are clay, mica and glass micro spheres. Although fillers increase the modulus of an un-reinforced matrix, they tend to reduce its strength and impact resistance [8].

Table (2-1): *Characteristics and limitations of the of thermosetting resins*

Resin Type	**Characteristics**	**Limitations**
Polyester	Wide choice of resins Cure at room temperature Very good mechanical properties Good chemical resistance Good electrical properties	Some shrinkage on curing
Vinyl Ester	Excellent mechanical properties Excellent chemical resistance Good fatigue resistance Good toughness Low water absorption	High cost Some shrinkage on curing
Epoxy	Excellent mechanical properties Very good chemical resistance Good thermal properties Very good electrical properties Low shrinkage on curing	High cost Long cure cycles Limited cosmetic properties

2.3 DURABILITY OF FIBER REINFORCED POLYMER

It should be noted that although the term durability is widely used, its meaning and implications are often ambiguous. Often it is erroneously taken to refer only to the weathering/degradation of a composite, whereas in reality this is only a small aspect of the overall phenomenon. FRP composites (and their constituents) can be affected by a variety of factors (including those related to the natural and surrounding environment), and the actual effect of each of these factors, or combinations thereof, can be substantially affected by the presence or absence of defects or other damage to the composite (or constituents thereof). A variety of different constituent materials are commercially available and the appropriate combination of these constituents allows for the development of a FRP composite system that provides the performance attributes for its intended use. In order to ensure that the term and its implications were completely understood for the purpose of the study, the durability of a material or structure was defined as ***its ability to resist cracking, oxidation, chemical degradation, de-lamination, wear, and/or the effects of foreign object damage for a specified period of time, under the appropriate load conditions, under specified environmental conditions.***

This concept is realized in design through the application of sound design principles and the principles of damage tolerance, whereby levels of performance are guaranteed through relationships between performance levels and damage/degradation accrued over specified periods of time. In this sense, damage tolerance is defined as ***the ability of a material or structure to resist failure and continue performing at prescribed levels of performance in the presence of flaws, cracks, or other forms of damage/degradation for a specified period of time under specified environmental conditions***. The overall concept is shown schematically in **Figure (2-2) [10]**.

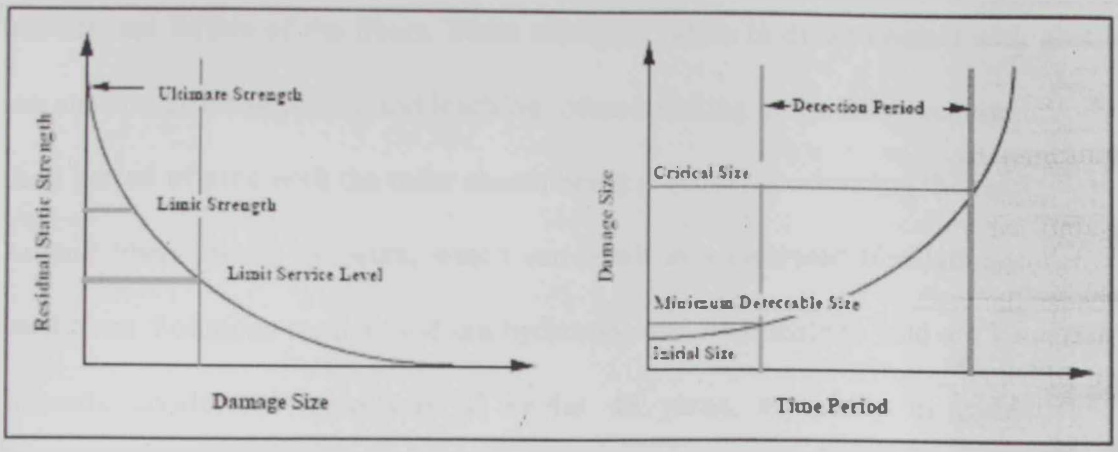


Figure (2-2): *Schematic Showing Application of Concepts of Durability and Damage Tolerance*

2.3.1 Influence of Moisture

FRP composites have a long history of use in marine vessels, piping, corrosion equipment, and underground storage tanks, and anecdotal evidence and limited testing shows that they can be successfully engineered to have long service lives in contact with moisture and aqueous solutions. It is, however, a misnomer that FRP composites and polymers are “waterproof” since moisture diffuses into all organic polymers, leading to changes in thermo physical, mechanical, and chemical characteristics. The primary effect of the absorption is on the resin itself that cause both reversible and irreversible changes in the polymer structure. In some cases, the moisture wicks along the fiber-matrix inter-phase and has been shown to cause deleterious effects to the fiber-matrix bond, resulting in loss of integrity at that level. Moisture and chemicals have also been shown in the case of aramid and glass fibers to cause degradation at the fiber level. In the case of glass fibers, degradation is initiated by moisture-extracting ions from the fiber, thereby altering its structure. These ions combine with water to form bases, which etch and pit the fiber surface, resulting in flaws that significantly degrade strength and can result in premature fracture and failure of the fibers. Basic solutions, when in direct contact with glass fibers, can cause significant pitting and leaching, often resulting in the fiber loosing its core over a short period of time with the outer sheath being reactive, accelerating the leaching process. Aramid fibers absorb moisture, which can result in accelerated fibrillation under specific conditions. Solutions such as sodium hydroxide and hydrochloric acid are known to cause dramatic accelerated hydrolysis of kevlar 49 yarns, especially in combination with temperature and stress. It is, however, possible to protect these fibers to a significant degree from rapid attack through the selection of appropriate resin systems, processing conditions, and the application of gel coats and protective coatings [11].

2.3.2 Alkaline Environment

There is a potential for degradation of FRP composites subjected to alkaline exposure in terms of both stiffness and strength values. Alkaline ions and moisture can diffuse through the resin matrix to the fibers and damage the FRP composite through a variety of mechanisms that will change based on the type of application, fiber, resin, sizing, and even process used to fabricate the product [12]. In using glass fiber composites in alkaline environment it is essential to ensure that high-alkali-resistant glass is used, because the alkaline solution reacts with glass fibers to form expansive silica gels. This precaution is especially important for application of glass-fiber-reinforcement composite material as reinforcing bars in concrete. Relatively inexpensive E-glass fibers are considered not to have much resistance against the alkali attack. Use of vinyl ester resin has been observed to reduce the alkali attack by providing an effective barrier. The resistance to alkali attack can also be improved by designing the member to lower stress levels. High-alkali-resistant glass can improve the durability. It must be noted also that carbon and aramid fiber composites are not susceptible to alkaline environment degradation [13].

2.3.3 Thermal Effects

FRP composites are subjected to thermal effects both during processing and throughout their lives. However, it must be acknowledged that process related effects in conjunction with post processing thermal exposure could have a significant effect on overall response and life cycle durability. It is acknowledged at the outset that not all thermal exposure is deleterious since in a number of cases it can actually result in much needed post-cure of FRP components, the response of both the resin and adhesive needs to be considered. It is noted that resins and adhesives soften over a temperature range, which causes an increase in viscous elastic response, a consequent reduction in elastic mechanical performance levels, and, in a number of cases, an increased susceptibility to moisture absorption. Prior research, materials testing, and anecdotal data has shown that in general:

- Sub-zero temperature exposure can result in matrix hardening, matrix micro cracking, and fiber matrix bond degradation.
- Freeze-thaw in the presence of salt can result in accelerated degradation due to the formation and expansion of salt deposits in addition to effects of moisture induced swelling and drying.
- Exposure to temperature above that of processing can result in an initial post-cure followed by degradation due to thermal effects [14].

2.3.4 Effects of Ultraviolet (UV) Radiation

Chemical changes induced by UV exposure are the result of a complex set of processes involving the combined effect of UV and oxygen. Bond dissociation is initiated by the absorption of UV radiation, resulting in chain scission and/or cross-linking; subsequent reactions with oxygen result in the formation of functional groups such as carbonyl (C=O), carboxyl (COOH), or peroxide (O-O). The effects of UV exposure, or photo degradation, are usually confined to the top few microns of the surface. However, in some cases, degradation at the surface of a polymeric component has been shown to affect mechanical properties disproportionately. It is a well-known fact that polymeric materials absorb in the ultraviolet region of the electromagnetic spectrum, and therefore are susceptible to reactions initiated by the absorption of ultraviolet energy. FRP composites are polymeric and are therefore prone to the same photochemical damage as un-reinforced polymers and polymer coatings. Increase the concentration of oxygen-containing functional groups and potentially lead to chain scission and/or cross-linking reactions. Chain scission reactions decrease the molecular weight of the surface polymers, allowing erosion of the low molecular weight fragments to occur. Continued exposure and subsequent erosion results in substantial loss of resin from the polymer surface, and in case of a FRP composite, the eventual uncovering of the underlying fibers. A common practice in outdoor applications of FRP composites is to use a gel coat or other protective coating to shield the surface of the FRP from direct ultraviolet exposure. However, it must be noted that the use of a polymeric protective coating does not prevent UV-induced damage from occurring, but serves as a "self-sacrificing" layer to prevent the FRP surface being directly exposed to UV radiation. The protective coating itself will eventually be degraded by UV radiation and will need to be maintained. Periodic inspections of the protective coating should be performed to ensure that the composite surface is not visible [15].

Chapter -3-

Chapter 3

Design Considerations for Strengthening Concrete structures by FRP

3.1 INTRODUCTION

Fiber reinforced polymer (FRP) materials are composite materials consisting of high strength fibers in a polymer matrix. The fibers in an FRP composite are the main load-carrying element and exhibit very high strength and stiffness when pulled in tension. An FRP laminate will typically consist of several million of these thin, thread-like fibers. The polymer matrix (sometimes referred to as the resin) protects the fibers from damage, ensures that the fibers remain aligned, and allows loads to be distributed among many of the individual fibers in the composite. There are a variety of fiber types and resins that may be used to create an FRP composite. Fibers are selected based on the strength, stiffness, and durability required for the specific application, and the resins are selected based on the environment the FRP will be exposed to as well as the method by which the FRP is being manufactured.

Among several possibilities, the fiber types that are typically used in the construction industry are carbon, glass, and aramid. *Carbon fibers* are the stiffest, most durable, and most expensive fibers. Typical carbon fibers used in the construction industry have strengths exceeding 10 times that of the typical Grade 60 steel used for reinforcement and over twice as strong as steel used for pre-stressing. The stiffness is similar to that of steel. Carbon is also quite resistant to environmental conditions and can withstand high sustained and fatigue loading conditions. Carbon is, however, is a conductive fiber material; and while carbon itself will not corrode, if it comes in contact with steel, it will accelerate corrosion of the steel. *Glass fibers* have lower strengths and significantly lower stiffness but at a reduced cost. At present, one of the concerns with glass fibers is durability. Unprotected glass fibers degrade in most environments, especially hot/wet or highly alkaline environments. Glass is also susceptible to a phenomenon known as creep rupture. This phenomenon results in the eventual failure of the material under sustained loads higher than a fraction of the instantaneous ultimate load.

At present, *aramid fibers* are the least common in the construction industry. These fibers have similar characteristics between those of glass and carbon but with improved durability and excellent impact resistance (hence why they are often used to make bulletproof vests).

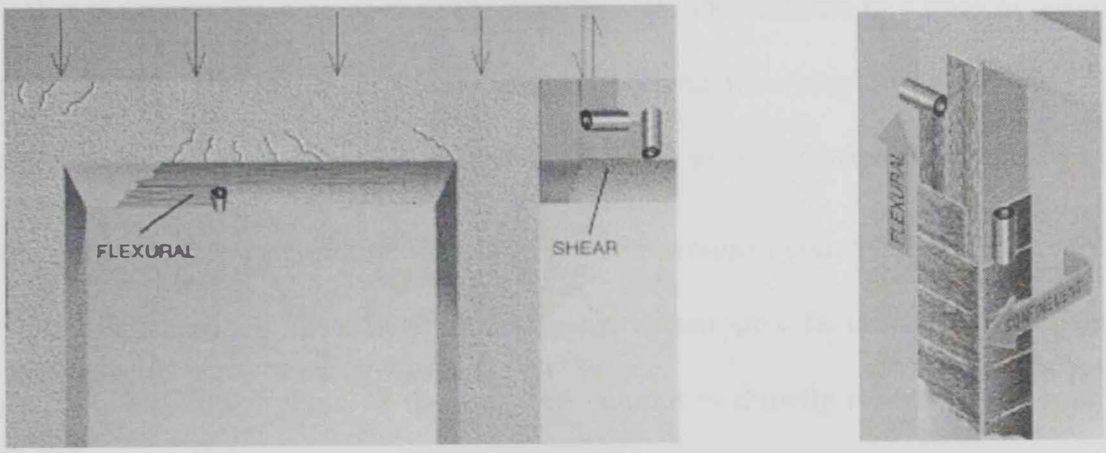
Resins used in FRP materials for construction industry, almost exclusively utilizes thermosetting resins. These resins start as a low viscosity, flow able material that cures to a final solid form. Epoxy and vinyl ester are the most commonly used thermosetting resins because of durability and adhesion properties **[16]**.

3.2 FRP FORMS FOR CONCRETE REINFORCEMENT

There is seemingly endless variety of forms that FRP reinforcement for concrete can take. ***For new construction applications***, *FRP bars, grids, and tendons* may be used. *FRP bars* are similar to steel rebar (often mimicking the shape and deformation patterns of rebar exactly). *FRP grids* are similar to welded wire fabric except that the grids may be three-dimensional. *FRP tendons* are used in place of steel tendons for pre-stressed concrete. The main advantage of FRP in new construction is durability. Since FRP materials do not corrode, FRP reinforced concrete may have an extremely long life. However, the cost of FRP materials is typically high in the new construction market and is only used in a limited number of applications.

For existing constructions, FRP systems used in repairing concrete to strengthen the structures. Structures may need strengthening due to deterioration, design/construction errors, a change in use or loading, or for a seismic upgrade. FRP essentially works as reinforcement in concrete and provides strength where concrete is weakest – in tension. FRP may be used on *beam or slab to provide additional flexural strength, on the sides of beams to provide additional shear strength, or wrapped around columns to provide confinement and additional ductility. Among many other applications, concrete and masonry walls may be strengthened to better resist seismic and wind loads, concrete pipes may be lined with FRP to resist higher internal pressures, and silos and tanks may be strengthened to resist higher pressures* **Figure (3-1)** and **Figure (3-2)** **[16]**.

In this research concentration will be only on the use of existing constructions especially beams on experimental chapter.



(a) *(b)*

Figure (a): *Diagram of Shear and Flexural Strengthening for Concrete Beams*

Figure (b): *Diagram of Flexural Strengthening and Confinement for Columns*

Figure (3-1)

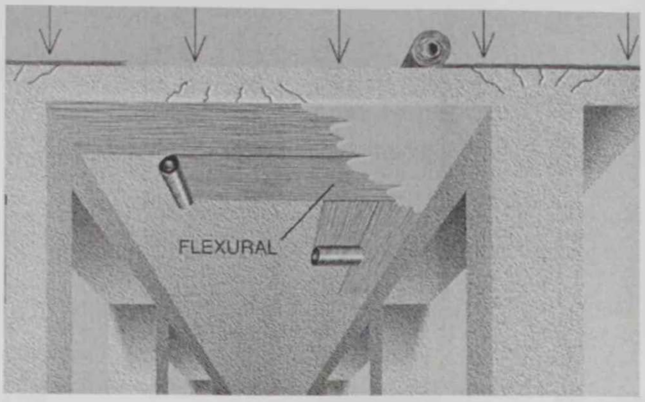
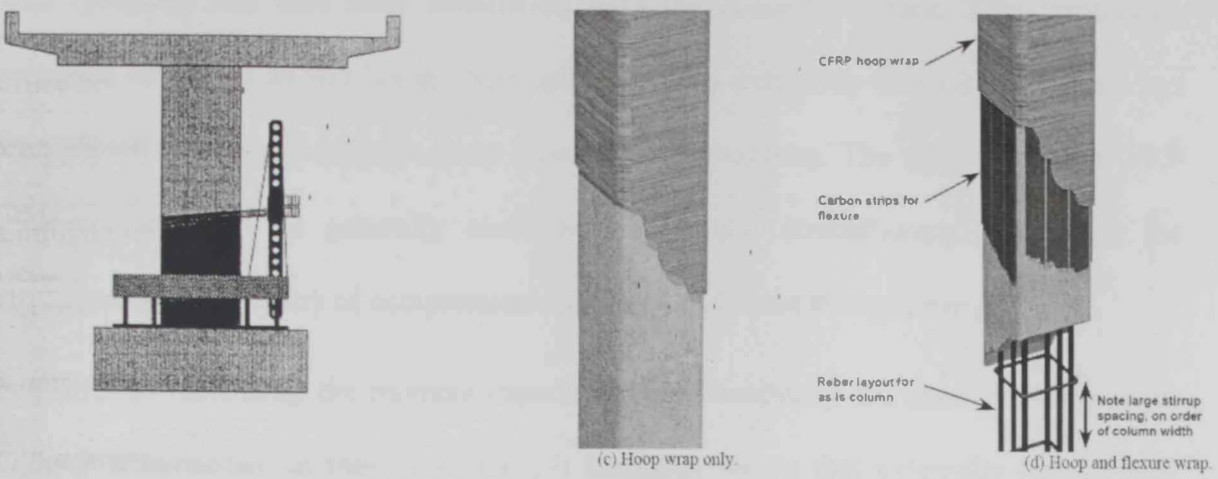


Figure (3-2): *Diagram of Flexural Strengthening of Slabs and Negative Moment Upgrade*

3.2.1 Composite Wrapped Concrete Columns

An extensive practice in large columnar concrete structure has been performed in site by using the automated FRP wrapping system, which was called *composites jacketing system*. FRP prepreg materials were laid up and cured automatically by applying pressure a heat simultaneously though the (Robo-Wrpper) machine **Figure (3-3) a**. It should be noted herein that the major function of the FRP laminates for the concrete in a state of tri-axial compression is to restrain its transverse dilation without involving heavy materials and equipment, which can cause the disturbance of traffic during maintenance operation.

However, the latest research found that the composite wrapped concrete column presented reduction strength and stiffness, and behaved more catastrophic failure under freeze-thaw cycle conditions. The strength of the confined column is directly related to the column shape, column with a sharp concrete is discouraged since premature failure by punching of the fiber may result. Use of high modulus wrapping materials for concrete confinement might result in increasing the hoop stress in the wrapping material at both end and bond; negative hoop stress may exist in the wrapping sheet and eventuate in causing tensile failure in a concrete column [17].



(a): *The composite jacketing system*

(b): *Composite wrap retrofit of column.*

Figure (3-3)

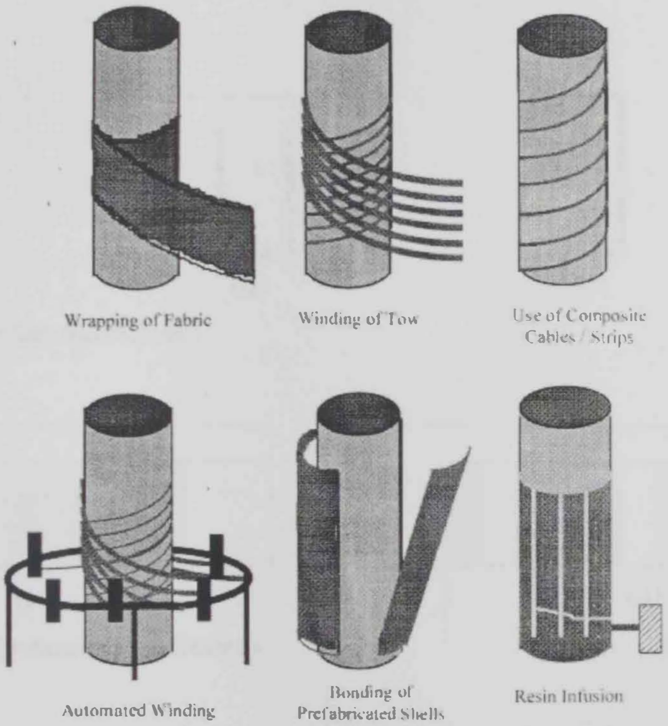
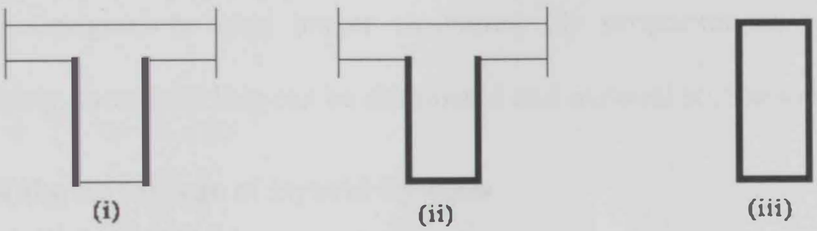


Figure (3-4): *Different system of wrapping column for repairing*

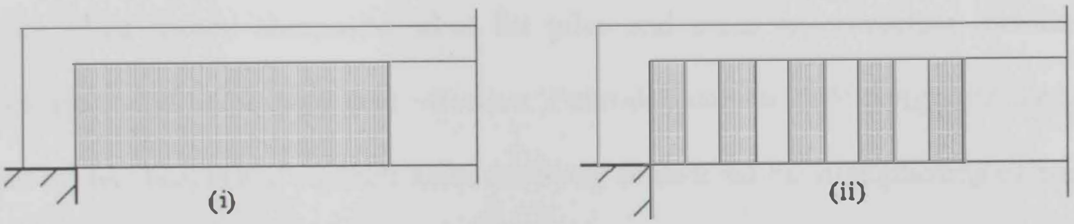
3.2.2 Composite Strengthened Concrete Beams

The laminates are stiff plates or shells that come pre-cured and are installed by bonding the plate to the concrete surface with epoxy. The sheets are either dry or pre-impregnated with resin (prepreg) and cure after installation onto the concrete surface. This installation technique is known as wet lay-up. Strengthening with externally bonded FRP sheets has been shown to be applicable to many types of RC structures. The uses of external FRP reinforcement may be generally classified as flexural strengthening, improving the confinement and ductility of compression members, and shear strengthening.

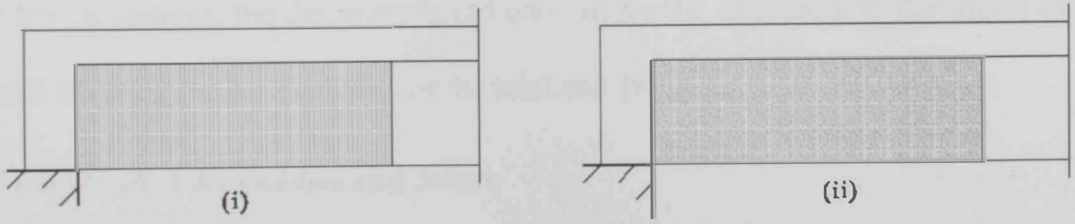
One limit to increasing the moment capacity is that eventually the shear capacity of the member is exceeded. In these situations, it has been shown that externally bonded FRP sheets may be used to increase the shear capacity as well. One of the difficulties with defining the shear contribution of FRP sheets is the wide variety of possible FRP shear reinforcement configurations **Figure (3-5) [18]**.



a: Bonded Surface Configurations.



b: CFRP Reinforcement Distributions.



c: Fiber Orientations.

Figure (3-5): *Shear Reinforcement Configurations*

3.3 DESIGN CONSIDERATIONS

3.3.1 Avoid Abrupt Thickness Change in Components

Because composites are viscosity materials, it is undesirable to create high stress risers. An understanding in the stress flow of a structural member will help a designer tailor the parts' thicknesses locally and avoid abrupt changes in its geometry [9].

3.3.2 Take Advantage of Geometrical Shapes

In most design using composites, the stress level is very low. An optimal design in composites balances the stress, deflection, and stability with the use of flanges, ribs, stiffeners, honeycomb or box-cells, or tubes to maximize the stiffness of the section. By placing flanges farther apart at the top and bottom of a hollow core, the section modulus can be designed to span longer structures. By proportioning and orienting the cells adequately, local buckling can be eliminated and material stiffness can be increased [9].

3.3.3 Take Advantage of Hybrid Systems

By taking advantage of the high stiffness in concrete and the high strength in composites, concrete filled carbon composite tubes for piles and main superstructure members in bridges are found to be very cost effective. Pultruded carbon FRP composite laminates bonded to steel beams and concrete slabs are being considered for strengthening of bridges. Composite fiberglass rods replacing reinforcing, bars in concrete bridge decks. With any of these hybrid systems, the designer should account for the difference in the strains of each material affecting the compatibility of the total unit [9].

3.3.4 Use Bonded Assemblies and Joints

Much work needs to be done in developing good joints to assemble the composite members by successful use of the epoxy adhesive technology. The concept of using epoxies shear transfer toggle strips has been demonstrated in two composite bridges, Plate bonding using epoxy adhesive on thin laminates to strengthen civil structures is seen as a promising application. The column wrapped with carbon tows (sheets) will be as strong as the epoxy bonded overlapping splice. The ability to advance the composite technology in civil structures will depend on the integrity and durability of these joints [9].

3.3.5 Provide Good Details for Connected Joints

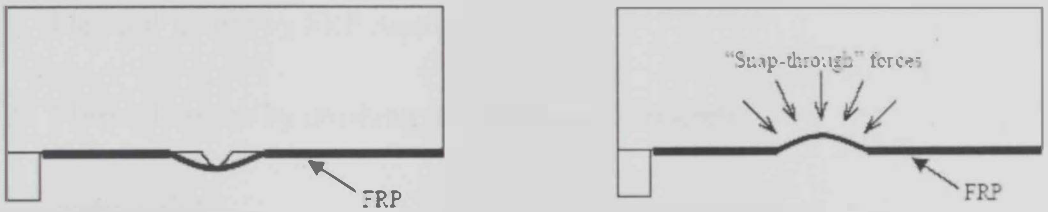
Special attention must be given to the local stress flow, overall load path, and joint lines that create weak links or porosity introduced during the manufacturing process. Other irregularities introduced during the cutting/drilling and fit up process must be evaluated. It is important to select proper fasteners. Certain composites with high flexural modulus are very brittle and have a tendency to granulate; they would not be suitable with screws. The ability to connect the components into a structural system will enable composites to go far in civil applications [9].

3.4 APPLICATION CONSIDERATIONS

It is critical to consider the condition of the existing concrete prior to encapsulation. FRP systems are often used as a solution to structural problems found when rehabilitating deteriorated concrete. Before any work is done, it is usually necessary to treat the existing structure in preparation for the FRP system, otherwise the bond quality and system longevity is at risk. It has been suggested that when using FRP plates or wraps rather then steel plates on chloride contaminated bridge beams; it is allowable to encapsulate the beam. This approach disregards the need to correct the interior reinforcement corrosion or concrete infiltrated with chemicals causing the damage, this "covering" is not sufficient and basic existing problems need to be addressed before FRP systems are implemented. By encapsulating the concrete we are not riding ourselves of the existing faults. Water and chemicals can still penetrate the concrete to further deteriorate the system and lead to bond failure between the FRP and concrete. Dilation of the concrete member due to corrosion induced cracking will eventually stress the FRP wrap and add unnecessary strain into the system. This action may accelerate the aging process of the FRP wrap. Also, FRP systems contribute to the structural system by adding tensile strength to the concrete, assuming adequate compression strength already exists. By wrapping weak, deteriorated concrete we do little to improve the quality of the overall structure. If the corrosion is allowed to continue it is likely that the concrete that the FRP is bonded to will spall prematurely due to increase in normal shear stresses and the expansive forces of the corroding steel. This phenomenon is often seen in beams and slabs. The existing concrete can be rehabilitated prior to FRP application by applying corrosion inhibitors and by repairing areas where the concrete may have spalled off. In cases of extreme deterioration, the mass of the structural element (usually columns) may need to be built up before FRP strengthening systems can be applied [19].

Other considerations factors effect on strengthening concrete by FRP system bond, namely, *bonded length, concrete strength, and number of plies (stiffness), sheet width and, to a limited extent, surface preparation*. Surface preparation very important step before application of FRP system if the FRP follows the contour of a hole, nap-through phenomenon caused by beam curvature can create a localized de-lamination, **Figure (3-6)**. There are mainly two types of concrete surface preparation either water jet or sandblasting. When water jet was used, the bond between the FRP and the concrete was significantly improved; the failure load was about 50% higher for the case of water jet surface treatment as compared to surface treatment by sander. It should be noted the jet water treatment crates much rougher surface as compare to sander treatment. And experimental study **[20]** on the effect of the type of fibers and the surface treatments o the bond strength of concrete specimens externally bonded to FRP sheets were performed. The following conclusions can be drawn from this study:

1. Externally bonded FRP sheets to prismatic reinforced concrete specimens increased both the tensile strength and stiffness.
2. The failure of specimens occurred near the interface between the FRP sheets and the concrete surface.
3. Results show that surface treatment by water jet produces a better bonding strength than surface treatment by sander.
4. Specimens reinforced with glass fiber sheet showed a lower average tensile stress than those reinforced with high modulus carbon fiber sheets. In addition, carbon fiber sheets of higher modulus produced high bonding strength than those with a low modulus.



(a): *FRP over a protrusion* (b): *Snap-through behavior of FRP bonded to contour*

Figure (3-6): *Surface preparation for FRP application*

3.5 FAILURE MODES OF FRP STRENGTHENED BEAMS AND SLABS

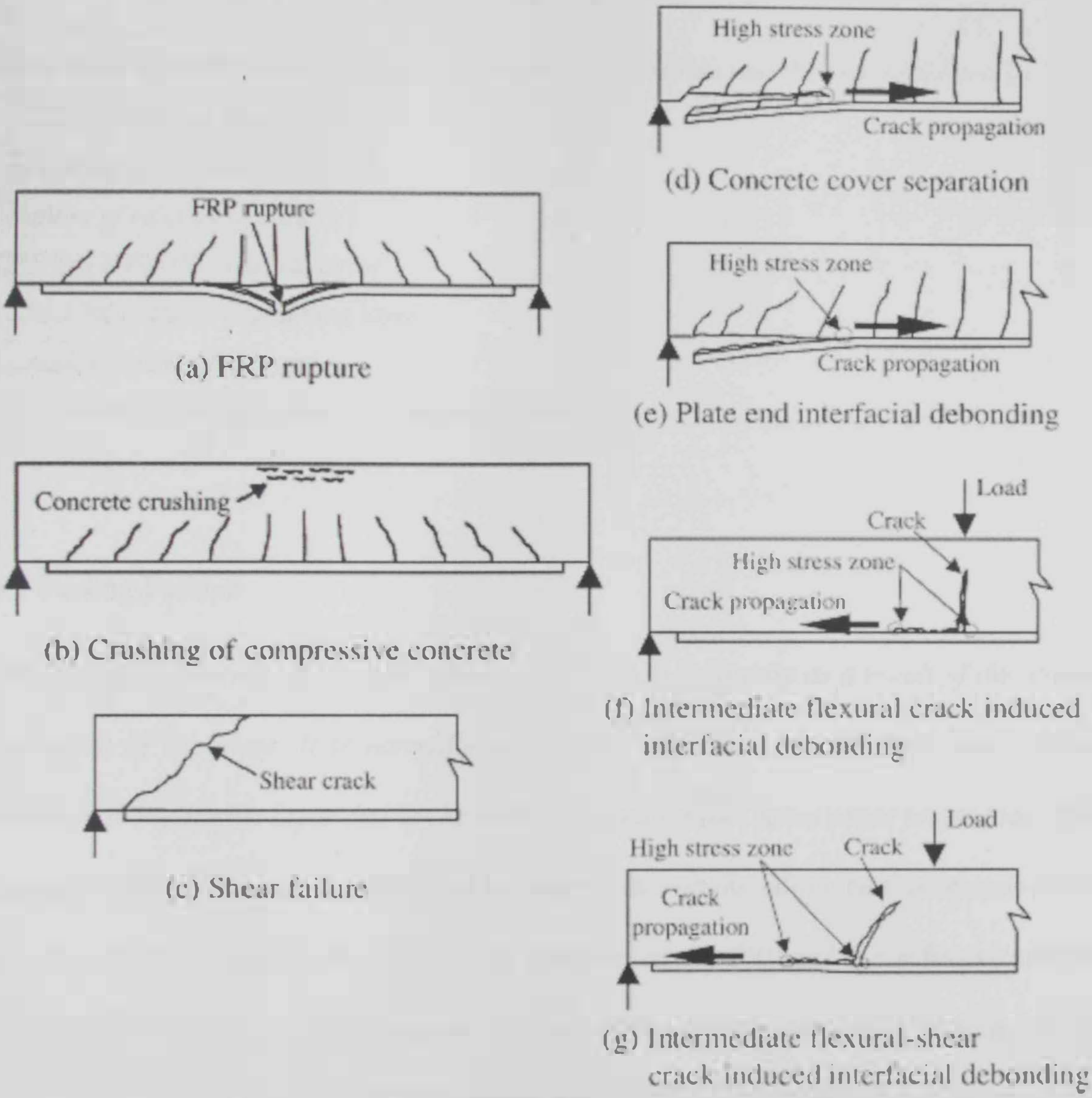
Failure of FRP strengthened beams may take place through several mechanisms depending on the beam and strengthening parameters. Recently, ACI Subcommittee 440F (2000) developed a report specifically on analysis and design and construction of externally bonded FRP systems. In this report, the failure modes of beams strengthened in flexure with external FRP reinforcement are classified as follows:

1. Concrete crushing before reinforcing steel yielding,
2. Steel yielding followed by FRP rupture,
3. Steel yielding followed by concrete crushing,
4. Cover de-lamination (peeling),
5. FRP de-bonding.

In addition to these, shear failure occurs if the shear capacity of the beam cannot accommodate the increase in the flexural capacity. An investigation of each of these failure modes is required in the design process to ensure that the strengthened beam will perform satisfactorily [21]. Based on existing studies, a schematic representation of seven typical failure modes observed in tests is shown in **Figure (3-7)**. These seven failure modes are termed and **Figure (3-8)** shows the location of weakness on concrete/FRP system:

1. Flexural failure by FRP rupture;
2. Flexural failure by crushing of compressive concrete;
3. Shear failure;
4. Concrete cover separation;
5. Plate end interfacial de-bonding;
6. Intermediate flexural crack induced inter-facial de-bonding;
7. Intermediate flexural-shear crack induced interfacial de-bonding.

Tests have shown that the load carrying capacity of RC beams flex rally-strengthened with an FRP plate bonded to the tension face is often limited by one of the de-bonding failure modes. The observed modes of de-bonding in FRP-plated beams can be broadly classified into two types: (1) those associated with high interfacial stresses near the ends of the bonded plate (failure modes (d) and (e)) which are collectively referred to as plate end de-bonding; and (2) those induced by a flexural or flexural-shear crack away from the plate ends (failure modes (f) and (g)) which are collectively referred to as intermediate crack-induced de-bonding [22].



(a) FRP rupture

(b) Crushing of compressive concrete

(c) Shear failure

(d) Concrete cover separation

(e) Plate end interfacial debonding

(f) Intermediate flexural crack induced interfacial debonding

(g) Intermediate flexural-shear crack induced interfacial debonding

Figure (3-7): *Failure modes of RC beams flexural-strengthened with an FRP soft plate [J.G. Teng , S.T. Smith , J. Yao , J.F. Chen, 2003].*

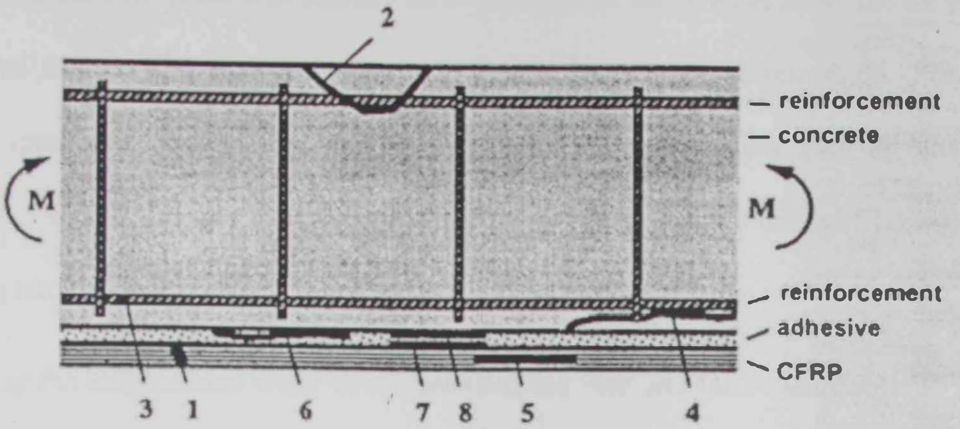


Figure (3-8) *Possible failure modes of a reinforced concrete member strengthened by FRP*

1 - Failure of carbon fibers

2 - Crushing of concrete

3 - Failure of reinforced bars

4 - Peeling off of the concrete cover

5 - Cracking in the strengthening layer

6 - Cracking in the glue layer

7 – De-bonding of the glue and strengthening material

8 – De-bonding of glue and concrete

3.5.1 Peeling Failure

Often occurs at the ends of the FRP where there is a discontinuity as a result of the abrupt termination of the plate. It is normally associated with concentrated shear and normal stresses in the adhesive layer due to the FRP deformation that takes place under load. The magnitude of these stresses is influenced by various factors including the dimensions of the FRP plate, the mismatch in the modulus of elasticity of the FRP and the adhesive and the shape of the bending moment diagram. Peeling failure usually results in ripping off the concrete cover along the level of the internal steel reinforcement toward the center of the member. Laboratory tests on plate beams have shown that the incidence of peeling failure will reduce if the tensile force in the FRP is allowed to increase gradually with distance from the end of the plate. This is akin to anchoring steel bars in concrete structures.

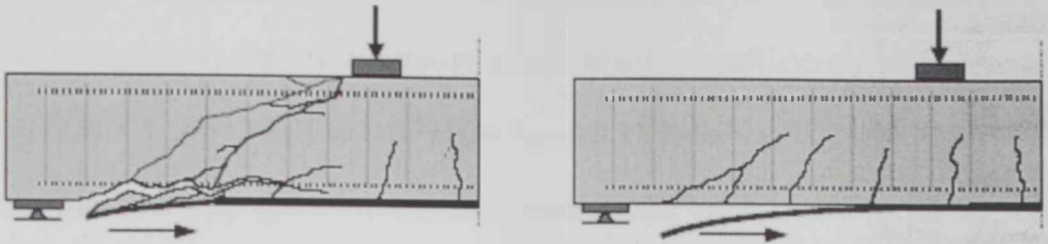
Also because the FRP plate will usually be terminated in the tension zone, the longitudinal shear stress at the FRP/concrete interface should be kept to a minimum. For simply supported members, this condition will be achieved by stopping the FRP as close to the support as possible. Generally, therefore, end plate separation failure will be avoided by addressing two criteria:

1. Limiting the longitudinal shear stress between the FRP and the substrate.
2. Anchoring the FRP extending it beyond the point at which it is theoretically no longer required

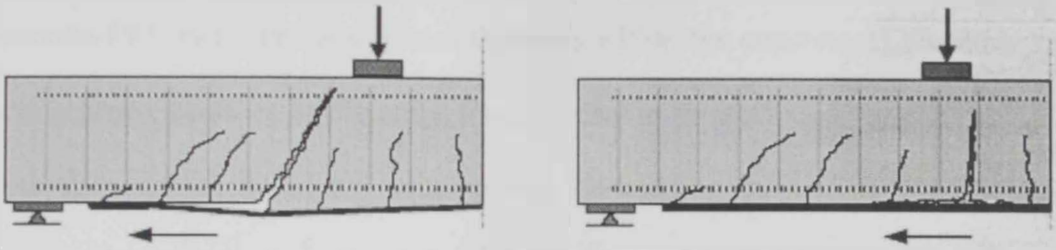
With regards to the first criterion, field experience of installing FRP systems suggests that, provided that the longitudinal shear stress at the ultimate limit state does not exceed 0.8 N/mm2, premature peeling failure will be avoided. The longitudinal shear stress should be checked at the plate ends, where the shear force acting on the strength ends potion of the member will be at its greatest. Additionally, the longitudinal shear stress should be checked at the location in the span where the steel reinforcement first yields. This is because beyond this point the elasticity of the steel is theoretically zero, and the tensile stresses due to the bending moment will be carried by the FRP alone **[23]**.

3.5.2 De-bonding

The term de-bonding failure is often associated with a significant decrease in member capacity due to initiation and propagation of de-bonding. *De-bonding initiation in beams strengthened with FRP composites generally take place in regions of high stress concentration at the concrete-FRP interface. These regions include the ends of the FRP reinforcement, and those around the shear and flexural cracks.* **Figure (3-9)** shows the fundamental de-bonding mechanisms that may result in premature failure of FRP strengthened beams. The cover de-bonding mechanism shown in **Figure 3-9a** is usually associated with high interfacial stresses, low concrete strength, and/or with extensive cracking in the shear span [21].



(a) cover debonding (b) FRP debonding from laminate end



(c) FRP debonding from flexure-shear crack (d) FRP debonding from flexural crack

Figure (3-9): *De-bonding failure mechanisms*

This mode of failure may occur also when the laminate is relatively thick (i.e. when more than one ply of FRP is attached to the concrete surface). The curtailment of the laminate adjacent to a support originates a high concentration of normal and shear stresses at the cutoff point of the sheet. Magnitude of these stresses depends on the geometry of the reinforcement, the engineering properties of the adhesive and tensile and shears strength of the concrete. In the case of RC beams strengthened with FRP sheets, the geometry refers to the number of plies (thickness of the FRP sheets) as well as the distance from the support to the edge of the sheets. When the principal stress associated to the peak of the normal (out-of-plane) and shear stresses exceeds the modulus of rupture of concrete, the failure will occur. Assuming fully composite action between concrete and the external reinforcement and un-cracked section derived them. The failure caused by this failure mode starts at the ends of the sheets, see **Figure 3-9a** and is induced by the high concentrations of stresses at that point. The development of the horizontal crack depends on flexural cracks, shear cracks and bond stresses along the steel reinforcement **[24]**. If the concrete strength and the shear capacity of the beam are sufficiently high, potential de-bonding failure is most likely to take place through FRP de-bonding, which initiates at the laminate ends and propagates towards the center of the beam, as shown in **Figure 3-9b**. Depending on the material properties, de-bonding may occur within the FRP laminate, at the concrete-FRP interface, or a few millimeters within the concrete. If the shear span of the strengthened beam is sufficiently long to enable proper bond development, or the laminate ends are anchored by some means, de-bonding may initiate at flexure-shear cracks and propagate towards the ends of the beam, as shown in **Figure 3-9d**. If the shear capacity of the beam is sufficiently high, de-bonding may also initiate from flexural cracks. However, this failure mechanism is very rare, especially in four-point bending tests. Propagation of de-bonding within the constant moment region does not change the stress distribution within the strengthened system; thus, a conceptual interpretation suggests that de-bonding propagation within the constant moment region is energetically not justified. It is possible, even expected, that high stress concentrations around flexural cracks may promote de-bonding, however, such stress concentrations diminish rapidly with propagation of de-bonding, resulting in a limited de-bonded area. For this reason, research into de-bonding from flexural cracks generally involves three point bending tests, which mechanically makes more sense. In four-point bending tests, de-bonding from flexural cracks close to the load points, i.e. close to the ends of the constant moment region, may propagate into the hear span and result in failure of the beam, which is a scenario similar to three-point bending tests. De-bonding failures in FRP strengthened beams are likely to involve a combination of the mechanisms described above, failure being determined by the dominant mechanism. A note worthy issue regarding the de-bonding mechanisms illustrated in **Figure 3-8 a-c** is the potential of shear failure in combination with de-bonding failure. It is often the case that the de-bonding and shear failures are not properly differentiated and reported. This is partly justified considering that the member is considered as failed in both cases. However, a fundamentally important difference between de-bonding and shear failures is the ductility behavior. De-bonding failures significantly reduce the beam capacity; however, provided that the beam has adequate shear capacity, it can still display the ductile failure behavior of an un-strengthened beam. This is not the case for shear failures where total beam failure takes place in a brittle fashion. Thus, it appears that ensuring adequate shear resistance of the beam must be considered as the first priority in strengthening design **[21]**..

3.5.3 Cover Tension

For externally bonded FRP reinforcement using sheet materials, the cover tension de-lamination condition starts developing at the location of flexural cracks and propagates towards the laminate end.

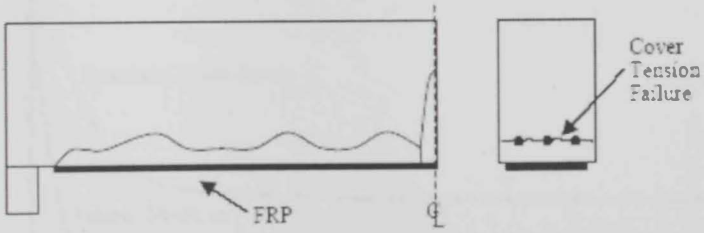


Figure (3-10): *De-lamination caused by tension failure of the concrete cover*

This is different from the case of bonded steel plates where the de-lamination usually starts at the plate end due to stress concentration and propagates toward the centerline of the beam. Because the reinforcing steel essentially acts as a bond breaker in a horizontal plane, the reduced area of bulk concrete pulls away from the rest of the beam. This situation is illustrated in **Figure (3-10)**. The use of over-wraps has been shown to lessen the effect of cover tension de-lamination. Over wraps are highly efficient if distributed over the length of the member. If the over-wrap is simply added at the at the FRP curtailment, its function is simply to add a safety device **[25]**.

3.5.4 Interfacial Shear and Peeling

Previous research on steel and FRP bonded plates has demonstrated that the interfacial shear and out-of plane tension (peel) distribution in the vicinity of the plate end to be significantly different than the average stress distribution. In situations where peel is the true failure mode, the difference between the local peak stresses and the average stress partially explains de-lamination. In the case of the curtailment zone for externally bonded FRP sheets, the stress distribution shown in **Figure (3-11)** may not be highly relevant due to the relative small thickness of adhesive and laminate. However, existing practice is to taper multiple sheets of FRP at 6 inches/ply **[26]**.

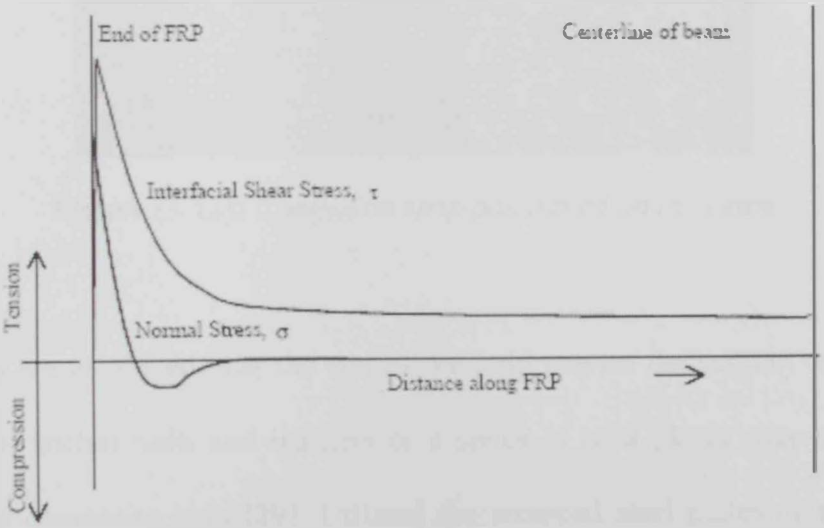


Figure (3-11): *Interfacial shear and normal stress distributions along the length of a bonded FRP laminate*

3.6 FAILURE SOLUTION

3.6.1 Flexural Strengthening of Beams with Fastened Method

In 1999, researchers introduced a new method of strengthening flexural members through the use of externally fastened FRP plates **Figure (3-12)**. Instead of using an epoxy adhesive, this method utilizes readily available commercial powder-actuated fasteners to attach a carbon-glass hybrid composite to the tension face of a reinforced concrete member. Tests on small-scale beams showed increases of strength similar to those of the bonded method. Subsequent experiments on large-scale beams revealed average strength increases of nearly 20% with the added benefit of more ductile failures **[27]**. The fastened method improves on the bonded method by reducing application time (no concrete surface preparation and no adhesive curing time) and reducing the sensitivity to environmental factors such as temperature and humidity during the repair process **[28]**.

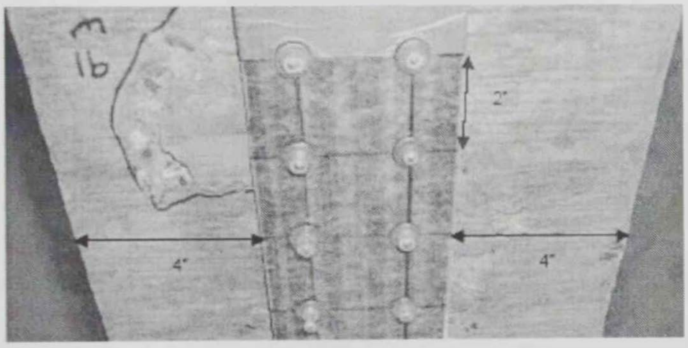


Figure (3-12): *Composite strip positioned on the beam*

These anchors are employed near the end of the strip nearest the support and are either a combination of anchor bolts and washers or a series of steel plates wrapped around and adhered to the composite strip **[29]**. Utilized the wrapped steel plates as anchors during testing and reported improved performance in the form of more ductile failures and increased load capacity up to 70%.

Despite pre-drilling both the composite strip and the concrete beam, researchers encountered significant spalling during the attachment procedure. As researchers “shot” the fasteners into the concrete, cracks formed and chunks of concrete broke away from the area surrounding the fastener. **Figure (3-13)** shows an example of typical spalling.

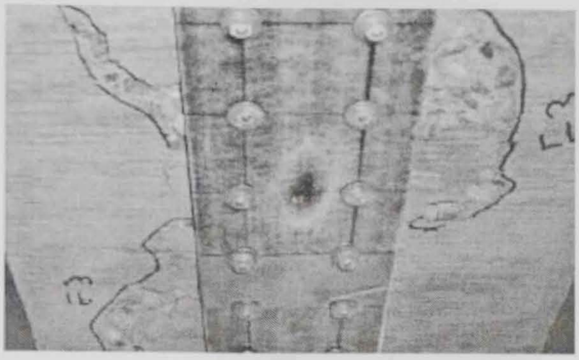
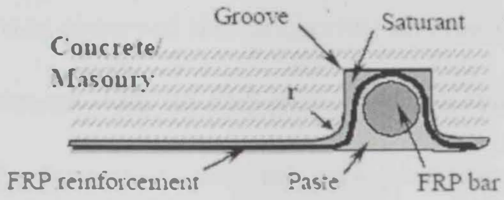


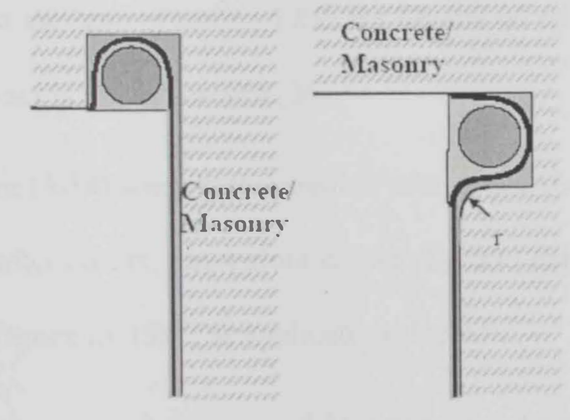
Figure (3-13): *Typical concrete spalling created while attaching composite strip*

3.6.2 Anchorage of Surface Mounted FRP for Externally Bonded Sheet

The method used to strengthen concrete beams with composite strips is similar to one that has been used with some popularity since the mid 1970s, particularly in Europe, to repair concrete beams with steel plates. In one popular method, the composite strip is bonded to the concrete surface with a room temperature curing two-part epoxy adhesive. The procedure for this method is time-consuming because it can take days per application to sandblast, clean, and smooth the concrete suitably for bonding. Other systems make use of preformed fiber fabrics and apply the epoxy resin system to the fabric and to the concrete substrate simultaneously. These systems require the same time-consuming and careful preparation and curing as in the case of bonding a prefabricated composite strip to the concrete. It has been claimed by a number of researchers that there may be a need to provide mechanical anchorage to the composite strip at its ends to prevent catastrophic brittle failure of the strengthened beam by strip detachment. The strip end anchorages have a greater effect in beams that are shorter than in longer beams. It has been recommended that strip end anchorages be used for all loading conditions. These mechanical anchorages are used to prevent peeling failures, and are not intended to be the primary load transfer mechanism between the concrete and the composite strip. The use of an entirely mechanically attached composite strip appears to be the next logical step in the development of research in this area. The use of multiple small fasteners, as opposed to large diameter bolts, distributes the load evenly over the composite strip and does not cause premature failure due to excessive stress concentrations at the holes in the composite strip Figure (3-14) [28].



(a) Anchorage to plane surface



(b) After corner anchorage (c) Before corner anchorage

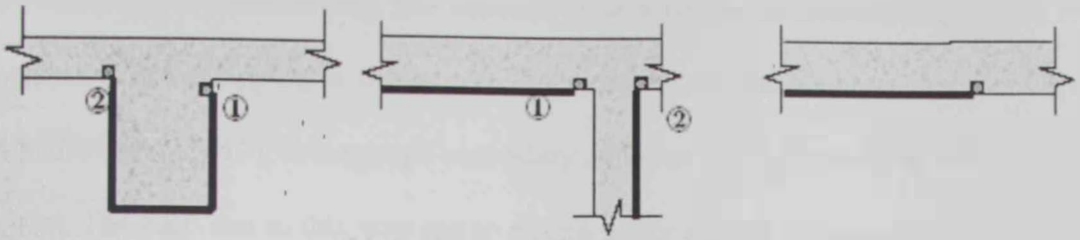
Figure (3-14): *Different application schemes of the U-anchor [Khalifa and Nanni, 1999]*

Although the use of externally bonded FRP composites has been implemented in many strengthening projects, there has always been a concern for the end anchorage. This is particularly important when the length of the FRP system is restricted and the bonded length beyond a critical section is not sufficient to achieve the ultimate strength of the FRP reinforcement. When FRP reinforcement is used for shear strengthening of rectangular or T-section RC beams, the FRP is applied to the sides of the section in the form of a U-wrap or strips with fibers perpendicular to the longitudinal axis of the beam. Shear cracks develop at approximately 45° with respect to the longitudinal axis of the member.

As a result, the FRP reinforcement may have minimal bonded length near the flanges of a T-section, usually leading to a premature failure due to de-bonding. This situation is even more critical in negative moment regions as cracks develop from the topside of the member. Premature failure could be prevented if sufficient end anchorage is provided. In the case of U-wraps, it was observed that anchoring increased the shear capacity by about 20% above that of specimens with no end anchorage. Mechanical anchors made of steel, although effective in the laboratory, are not very practical for field application due to drawbacks such as stress concentration and, in the case of bolting, discontinuity of the FRP at drilling locations. In the case of carbon FRP, the likelihood of galvanic corrosion due to steel-carbon fiber contact is also a concern [30].

The sketches of **Figure (3-14)** show three possible uses of the U-anchor: away from corner (on a plane surface), after corner, and before corner. Typical applications of the U-anchor system are shown in **Figure (3-15)**. The applications include:

- Before and after corner end anchors of U-wraps for shear strengthening of beams **Figure (3-15a)**
- Before and after corner end anchors of sheets for flexural/shear strengthening of walls and columns **Figure (3-15b)**
- Plane surface anchorage of sheets for flexural strengthening of beams and slabs **Figure (3-15b-c) [30]**.



(a) Anchor types for U-wrap shear strengthening of beams

(b) Anchor types for flexural strengthening of beam/slabs and wall columns

(c) Plane surface anchorage for flexural strengthening of beam/slabs

Figure (3-15): *Example of application for anchorage system [Khalifa and Nanni, 1999]*

3.7 DURABILITY OF CONCRETE/FRP SYSTEM

The anchorage between concrete and FRP laminates plays an important role in reinforcing design. As a brittle material, FRP shows a lack of ductility, and the failure mode occurs suddenly without preceding yielding. In cases when the bond rupture or anchorage rupture is unavoidable, it is necessary to obtain the rupture strength experimentally, based on reliable data that adequately consider safety factors. In a pure tensile experiment, the bond strength at average stress has the tendency to decrease when the bond area increases. This occurs because the bond stress is not distributed throughout the full area of the bond length. It has been reported by previous studies that the bond stress is distributed in the region from the loaded end of the laminate, or from the crack position, with a length not more than 100mm from those points [31]. Investigated bond between concrete and FRP plates used to be as connections in pre-cast concrete walls. Failure occurred due to one, or a combination, of the following modes: FRP rupture, de-lamination of the FRP from the concrete and concrete surface shear failure.

3.7.1 Accumulation of Water

Harmful materials, such as acid rain and siliceous particles, can be transported through concrete pores and cracks by water. If excess water is allowed to accumulate or pool along the concrete or it's reinforcing, the concrete is at a risk of accelerated aging and reduced function. When wrapping or lining with FRP rehabilitates the concrete member **Figure (3-16)** and **Figure (3-17)**, the epoxy's secondary function of waterproofing inhibits moisture transfer. The FRP can in this way entrap excess water against the concrete and increase the risks of deterioration. As gravity forces the water downward, water builds up between the FRP and the concrete, unable to dissipate. This is also true for the underside of slabs that have upper surface cracks where water can enter and pool on the substrate against the FRP. In these cases we often see bubbles of excess moisture and deteriorated epoxy bonding, such as on epoxy coated concrete floors, slabs and painted walls [32].

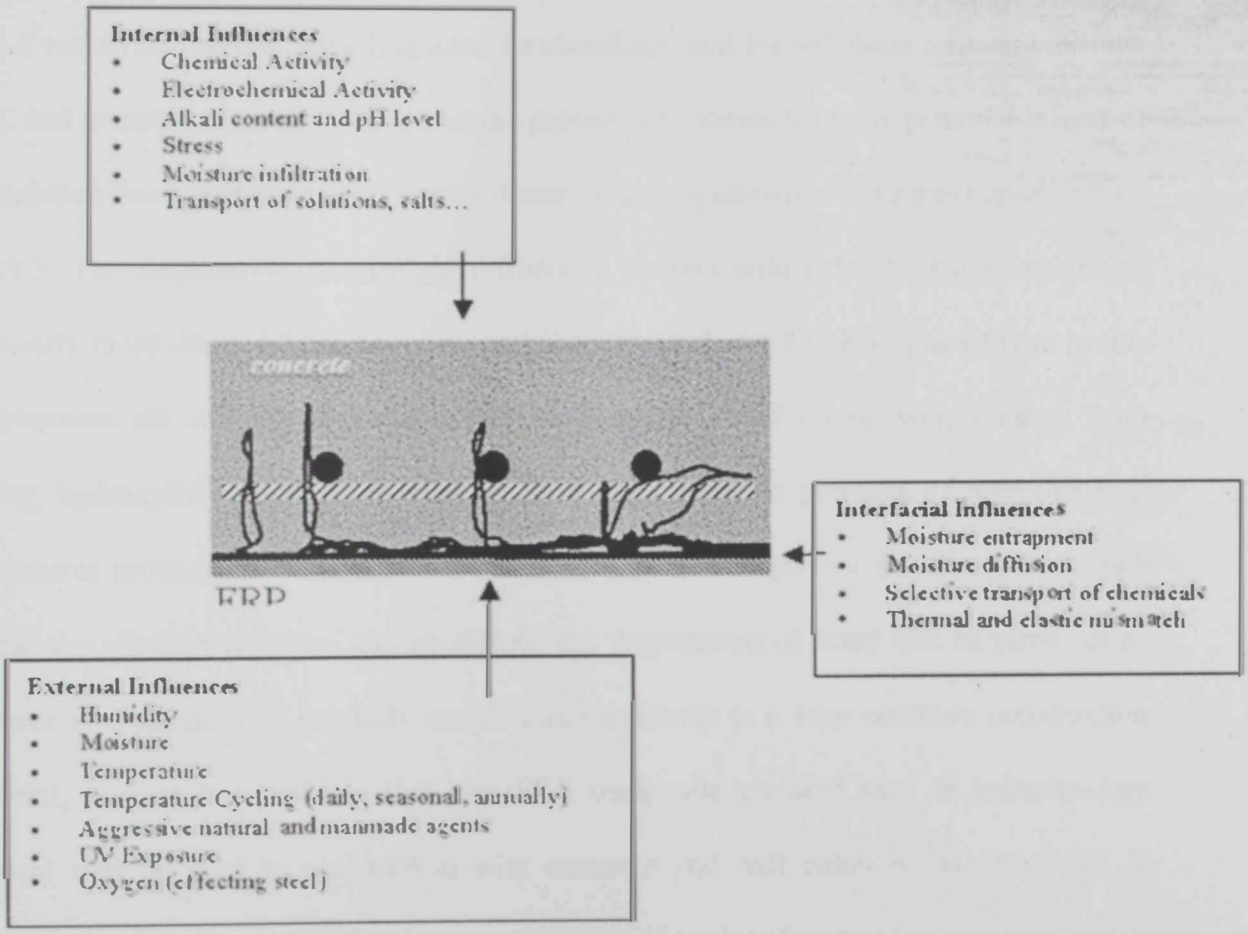


Figure (3-16): *System level interaction (Karbhari 1997)*

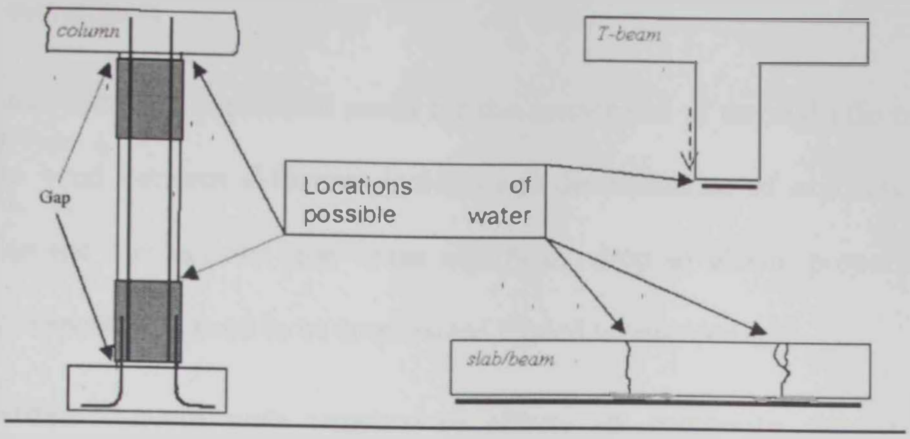


Figure (3-17): *Schematic of Water Infiltration Locations*

3.7.2 Alkaline Environment

Although FRP composites can come in contact with alkaline media through interaction with a variety of sources, including alkaline chemicals, soil (or solutions diffusing through soil), and concrete, the main concern at the present time stems from the potential effects of degradation due to concrete pore water solution, which is known to have a pH level as high as 13.5. The degradation of bare glass fibers in contact with (or in) alkaline solutions, especially those derived from concrete, and there is no doubt that bare glass fibers in this environment are severely degraded due to a combination of mechanisms ranging from pitting, hydroxylation, hydrolysis, and leaching. Although the presence of resins in FRP composites around individual filaments can be expected to protect the fibers from such attack, the alkaline solutions can accelerate the degradation of bond and of some resins themselves, especially if not fully cured. Since concrete is a very common construction material, it is highly probable that any FRP composite element used in infrastructure renewal will be used in conjunction with concrete and will either be a) embedded in concrete (as in the case of rebar or tendons), b) placed around concrete thereby encapsulating it (as in the case of column strengthening), or c) in direct contact with concrete as a substrate (as in the case of rehabilitation of beams and slabs) [12].

3.7.3 Thermal Effects

It is noted that there are significant needs for the assessment of thermal effects especially as related to bond between different elements and determination of exposure levels and resulting damage mechanisms that cause significant drop in elastic properties of FRP composites. Aspects that need to be emphasized related to this area are:

1. The greatest concern with temperature effects on composite structures in civil engineering applications is that freeze-thaw conditions can potentially result in de-bonding of laminates, either from concrete, or from other FRP composite elements, particularly if there are gaps at the adhesive bond line. Installation guidelines should stress surface preparation. Tap testing new installations for gaps in the adhesive bond line, or un-bonded regions, is recommended.
2. Failure is also possible if the laminating resin or adhesive softens excessively. The upper use temperature, a given laminating resin is defined as the temperature at which the flexural strength decreases to half the room temperature value. Polyester and vinylester laminates generally soften at temperatures above those expected in service. Orthophthalic polyesters have the lowest upper use temperatures of this class, 160-180°F. Isophthalic polyesters soften between 180-200° F and (most) vinylesters soften above 200°F. Room temperature curing epoxy resins have relatively low material operational limits, typically 120-160°F, so particular attention should be given to the service environment of epoxy laminates.
3. FRP composites should not be used at temperatures above their glass transition temperatures, and for purposes of design it is recommended that materials be chosen that have a T_g at least 86 ° F (30°C) above the maximum use temperature.

4. The synergistic effects of moisture/solution and thermal effects need to be further considered, with investigations into both materials and structural systems response changes. Effects on under-cured systems need to be assessed especially as related to changes in creep compliance, toughness, and mechanical performance in shear.
5. Long-term effects of differences in thermal coefficients expansion and elastic properties of bonded materials need to be considered. Effects of the presence of large heat sinks as with concrete need to be assessed both for in-process and post-process effects [14].

3.7.4 Ultraviolet (UV) Radiation Effects

In the majority of outdoor applications, FRP composites are protected with a gel coat, which is a resin-rich layer applied to the surface of the composite. Its function is to delay the effects of UV exposure by lengthening the time period before the FRP surface is exposed, but it will not prevent the damage from occurring and progressing. Repair generally involves the application of a fresh gel coat or resin layer. FRP composites are polymeric and are therefore prone to the same photochemical damage as un-reinforced polymers and polymer coatings. Photochemical reactions in polymers, generally limited to the topmost 50-100 microns, increase the concentration of oxygen-containing functional groups and potentially lead to chain scission and/or cross-linking reactions. Continued exposure and subsequent erosion results in substantial loss of resin from the polymer surface, and in the case of a FRP composite the eventual uncovering of the underlying fibers. A common practice in outdoor applications of FRP composites is to use a gel coat or other protective coating to shield the surface of the FRP from direct ultraviolet exposure. However, it must be noted that the use of a polymeric protective coating does not prevent UV-induced damage from occurring, but serves as a "self-sacrificing" layer to prevent the FRP surface being directly exposed to UV radiation. The protective coating itself will eventually be degraded by UV radiation and will need to be maintained. Periodic inspections of the protective coating should be performed to ensure that the composite surface is not visible [15].

3.8 FIBER SELECTION FOR REINFORCING CONCRETE STRUCTURES

The most suitable fibers for strengthening applications are glass, carbon or aramid. Each is a family of fiber types and not a particular one. It should be noted that these values are for the fibers alone, not for fiber composites, the values in **Table (3-1)** should only be taken as indicative where necessary, actual values should be obtained from the manufacturer. The fibers all have a linear elastic response up to ultimate load with no significant yielding.

(Table 3-1): *Typical fiber properties.*

Fiber	Tensile strength (N/mm^2)	Modulus of elasticity (kN/mm^2)	Elongation (%)	Specific density
Carbon: high strength	4300-4900	230-240	1.9-2.1	1.8
Carbon: high modulus	2740-5490	294-329	0.7-1.9	1.78-1.81
Carbon: ultra high modulus	2600-4020	540-640	0.4-0.8	1.91-2.12
Aramid: high strength and high modulus	3200-3600	124-130	2.4	1.44
Glass	2400-3500	70-85	3.5-4.7	2.6

Performance of different types of fiber: the selection of type of fiber to use in a particular application will depend on many factors – the type of structure, the expected loading and environmental conditions. Further advice can be obtained from suppliers of strengthening materials. Throughout the comments refer to the performance of the fiber itself in most situations this will be modified by the resin or adhesive.

Chemical resistance: carbon and aramid fibers are resistant to most forms of chemical attack. Many type of glass fiber are attacked by alkalis (pH greater than about 11) but not by acids. Aramid absorb much more water than either of the other two fibers which ca cause problems with the resin/fiber interface. There is some evidence to suggest that in the presence of salts fracture of all types of fiber can occur due to the formation of angular crystals.

Resistance to ultraviolet light: glass and carbon fibers are not affected by ultraviolet light. Aramid fibers change color under ultraviolet light and the strength is reduced. However, when embedded in a resin matrix the degradation only occurs near the outer surface and there is little effect on the overall mechanical properties. (Direct exposure to sunlight can embitter all resins and protective paint is normally recommended if erect exposure).

Electrical conductivity: aramid and glass fibers are non-conducting and hence are suitable for use close to power·lines, lines and communications facilities. Carbon fibers conduct electricity but standards have been issued in Japan for the use of carbon FRP strengthening materials in railway applications close to power lines. They must be electrically isolated from any steel reinforcement; in general the resin will be sufficient for this. Care is needed when handling or cutting carbon FRP close to electrical equipment due to the risk of short-circuit by airborne particles. In addition, when used close to power lines etc, steps must be taken to ensure that in the unlikely event of adhesive failure, the composite does not come into contact with the electrical source.

Compressive strength: the compressive strengths of carbon and glass fibers are close their tensile strengths that of aramid are significantly lower.

Stiffness: the elastic modulus of carbon fiver is similar to or significantly greater than that of steel. The stiffness of aramid is lower and that of glass significantly lower.

Impact resistance: performance of fibers during impact is highly dependent on the elastic strain energy greater and absorbed. Fibers combining high strength with high elongation (tensile strength greater than 3500 N/mm^{2}and elongation greater than 2%) are most suitable for applications where impact resistance is important. Selected grade of carbon, aramid and glass fiber can meet these requirements.

Fire: glass fibers retain strength up to their melting point (over 1000°C) while carbon fibers oxidize in air above 650°C. Aramid fibers are not normally used above 200°C. None of the fivers will support combustion. In composites, the resin behaviors will dominant performances most generate toxic smoke [23].

3.9 REPAIR OF FRP COMPOSITES

As with any construction material, FRP composites are subject to damage. This damage may be intentional or unintentional. Intentional damage can occur when the composite components or structures are cut, drilled, or otherwise manipulated during installation or fabrication of the structure. Accidental impact, unexpected excessive loading, or long-term environmental exposure can cause unintentional damage. It is important to note that any damage or alteration to the fibers and/or the resin matrix may alter the performance properties (e.g., corrosion resistance and mechanical strength) of the composite component. The following information addresses the repair of composite materials needed as a result of damage or deterioration due to installation procedures, accidental damage, or environmental exposures.

3.9.1 Routine Maintenance

a. A properly designed and fabricated composite system will generally not require much in the way of routine maintenance. For aesthetic purposes, soil and other similar surface contaminants may be washed off using plain water [including steam cleaning at

120° C (250° F) maximum] or a detergent solution. Greases and oils may require cleaning with an appropriate organic solvent (ion that will not attack the resin system).

b. Composites intended for direct exposure to weathering and ultraviolet radiations generally have a surface coating to improve corrosion and ultraviolet resistance. Under Long-term weathering, especially if the original coating was too thin, fiber blooming (i.e., the emergence of fibers onto the surface) can occur. If left unattended, fiber bloom can lead to reduced corrosion resistance and eventual degradation of mechanical properties.

c. If fiber bloom is identified, the damaged area must be resealed with a resin-rich layer. The damaged area must be lightly sanded and cleaned to ensure proper adhesion of the sealant. Catalyzed resins or paints (e.g., polyester, epoxy, or polyurethane) may be used. A general rule is to use a sealant material type that is the same type as on the component being repaired. Acrylic lacquer or oil base paints can also be used but will probably not provide the same level of corrosion resistance as a catalyzed resin system. As required when using any chemical system, manufacturer's instructions must be closely followed to provide an optimum repair and to minimize the exposure to potentially hazardous materials.

3.9.2 Repair During Installation

Sawing, drilling, grinding, routing, and other such procedures may be necessary to accomplish installation or fabrication of the composite structure. Any such procedures that cut through the resin surface sealant, or otherwise expose the reinforcement fibers, can significantly reduce the corrosion resistance of the FRP system. The exposed new surface must be appropriately sealed. To ensure a proper repair, residual dust or other debris resulting from the installation operations must be removed prior to the repair procedures.

3.9.3 Repairs Due to Accidental Damage and/or Service Exposures

Damage to the composite component can result from impact of falling or flying objects, unexpected excessive loading(s), handling of the composite during transportation, and installation or degradation (e.g., blistering) due to service exposures.

a. Visual inspection will be the most often method used in locating damage on civil structures. Such visual inspections should be performed on a routine, periodic basis so damaged areas can be repaired before further deterioration to the composite component occurs. Ultrasonic and various other NDE methods are available to detect hidden damage.

b. Once the damage detected/located and the extent of the damage determined, damage repair options must be considered. If the damage is exposed but is only a surface scratch or abrasion, the repair may be as simple as coating the area with a resin-rich coating as previously described. If hidden damage is detected and it is determined that the damaged area is not a critical load-bearing component, an assessment must be made as to whether the damaged area is likely to grow, thus warranting an immediate repair. If a repair is determined to be unwarranted at the time, the damaged area should still be monitored to assess possible growth of the damage to adjacent areas.

c. Damage to critical structure components will require immediate repair action. Basic repair options include:

    (1) Patching with composite plates or overlays.

    (2) Removing the damaged area or component and replacing with new material.

d. Localized minor cracks and punctures may be repaired using lay-up procedures similar to automotive body repair. The damaged area must first be sanded to roughen the surface. Lightly sand the surface 50-75 mm beyond the immediate damaged area.

A fiber mat shall be cut to cover within 13 mm (1/2 in.) of the edge of the sanded area. Thoroughly wet the fiber mat with a catalyzed resin system compatible with the composite component being repaired. Multiple layers may be applied as needed. After curing, sand the area to a smooth finish and seal

e. If the extent of damage is considered beyond just applying a patch, the damaged section will need to be removed. The removed section may then be replaced with a new section or component. This may be as simple as bolting on a new beam or angle, or may require the laminating in of a new composite section. To ensure equal mechanical performance, the repair section must have the same fiber architecture (orientation and arrangement) and section thickness as the removed section.

3.9.4 Underwater Repairs

Emergency situations or other site conditions may make it impossible to dewater or ~move the composite structure from submersion in order to accomplish a repair. Under such circumstances, specially formulated resin systems and special procedures must be used for an underwater repair. Except for the repair of relatively minor damage, expert advice should be sought before attempting any major underwater repair procedures. The non-ideal conditions of performing underwater repairs call for a high level of quality control during repairing. Under most circumstances, underwater repairs should be viewed as a temporary measure until such time that permanent repair in dry conditions could be made [33].

Chapter -4-

Chapter 4

Experimental Results and Analysis

4.1 EXPERIMENTAL PROGRAM

There are two main objectives of this experimental program:

1. The use of FRP for strengthening of plain concrete beams
2. Investigating the degradation mechanisms for FRP used for repair and strengthening.

Strengthening materials was supplied by the FOSROC Company; it consists of a unidirectional carbon fabric having a surface weight density of 300 g/m^2. The fabric is supplied in sheets having a width of 500 mm and a ply thickness of 0.165 mm/ply. Also the company supplied the impregnating resin system, which is made up of a primer (Nitobond EP) and a resin (Nitobond EP10). The primer has a pot life of 45 min at 20° and the setting time is within 11 hours. Its viscosity at room temperature is close to 1300 cp and no solvent was added to the primer. The resin has the same characteristics as the primer except for the viscosity, which is much higher (≈ 5000 cp).

In addition to carbon fibers, two types of glass fabric reinforcements were used. The first one was made up of unidirectional glass fiber tows and having a surface density of 435 g/m^2. The second one was also made of unidirectional tows but an aramid tow was added in the weft direction, the reinforcement has a surface weight density of 913 g/m^2. .

4.1.1 Strengthening of Plain Concrete Beam using FRP

Plain concrete beams were cast (500 mm x 500 mm x 100 mm) using both seawater and normal water. After full curing, specimens were subject to flexural testing using a three point bending test set-up. As there is no reinforcement in the beams, the damaged beams under flexural bending test crushed as shown in **(Figure 4.1)**.

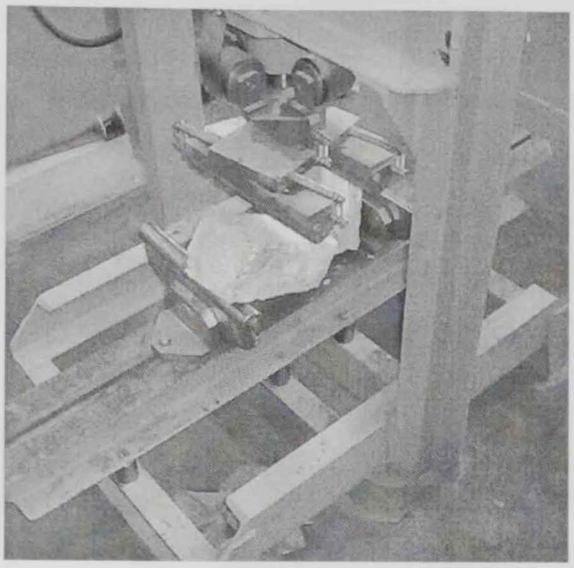
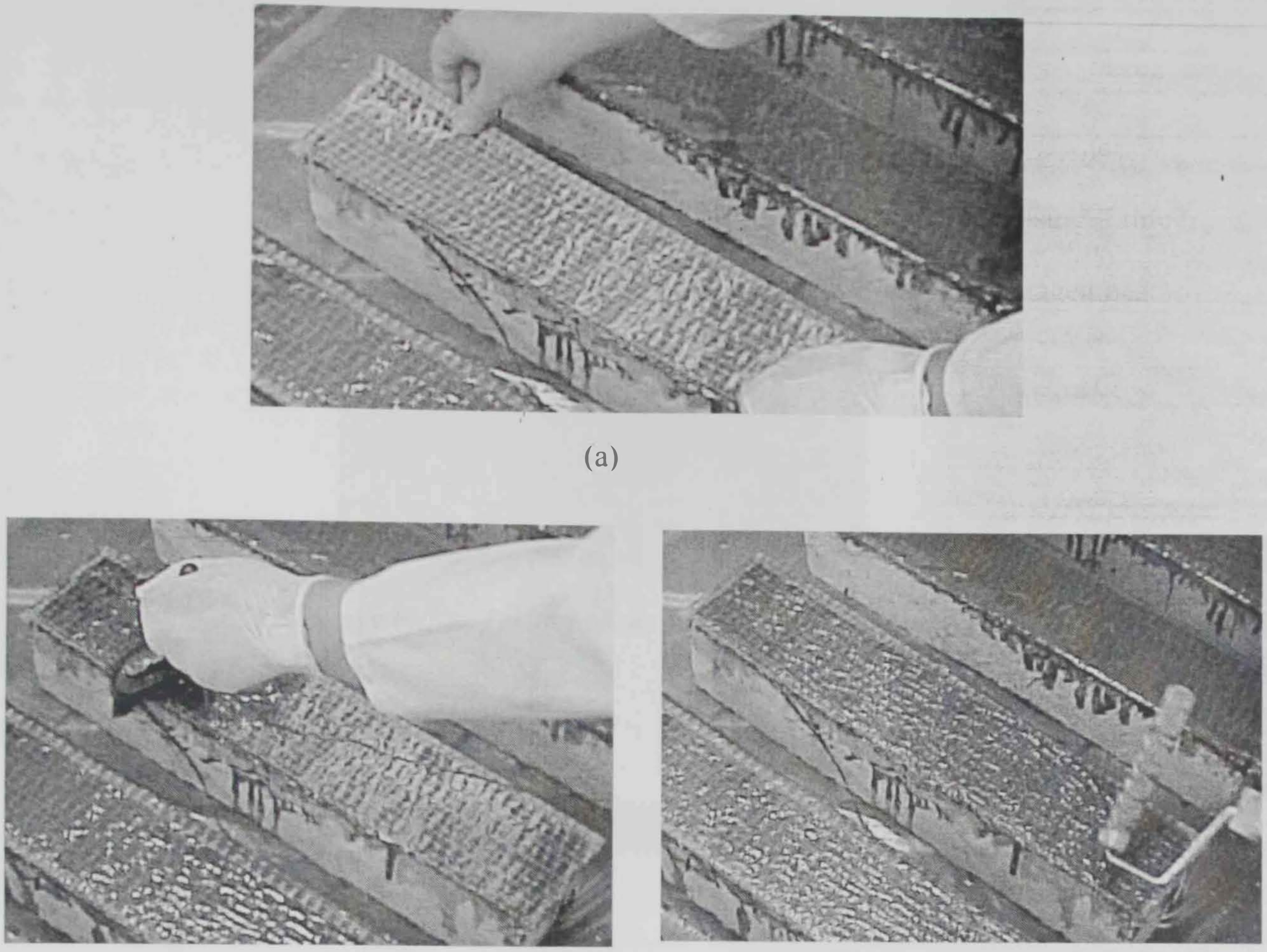


Figure (4.1): *Fracture of the plain concrete beam.*

The damaged beams were then reinforced using three layers of unidirectional carbon fabric. The procedure for strengthening these beams was the standard one recommended by the manufacturer (FOSROC). The main steps can be summarized as follows:

The beams were sand blasted on one of their face, then a primer was applied in order to fill the holes and the grooves that are present on the surface, in addition to create a good bond between the concrete and the composite layers. Then three ply of carbon sheet having the dimensions of the beams were hand laminated on one face of the beams. Once this operation is completed, specimens were left for complete curing for a minimum of one week. **(Figure 4.2)** summarize the different steps of beams strengthening.



(a)

(b) (c)

Figure (4.2): *Different steps involved in the strengthening of cracked concrete beams: (a) (b) and (c) positioning and application of the reinforcement and epoxy resin.*

Once the strengthened beams reached full cure, they were subject to new testing as shown in **(Figure 4.3)** It is worth to notice that no significant difference occurred in term of the maximum fracture load between the specimen cast using seawater **(6.5 KN)** without FRP **(46.5 KN)** with FRP and that using normal water **(6.12 KN)** without FRP **(39.2 KN)** with FRP. It is clear that by adding the composite layers, a substantial improvement occurred in the load carrying capacity of the beams as shown in the data presented in **(Figure 4.4)**, where by using FRP to strengthen the completely deteriorated (crushed) beams, the maximum fracture load increased 7 times.

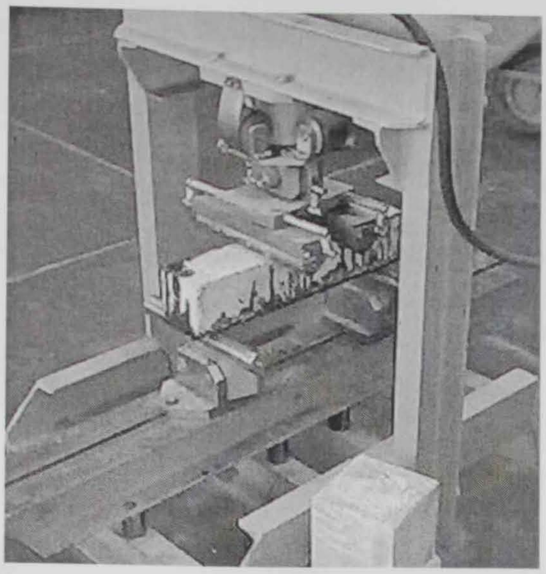


Figure (4.3): *Testing of the strengthened beam*

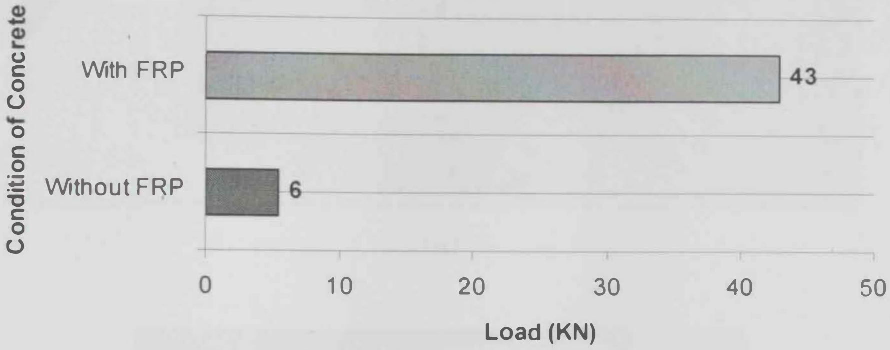
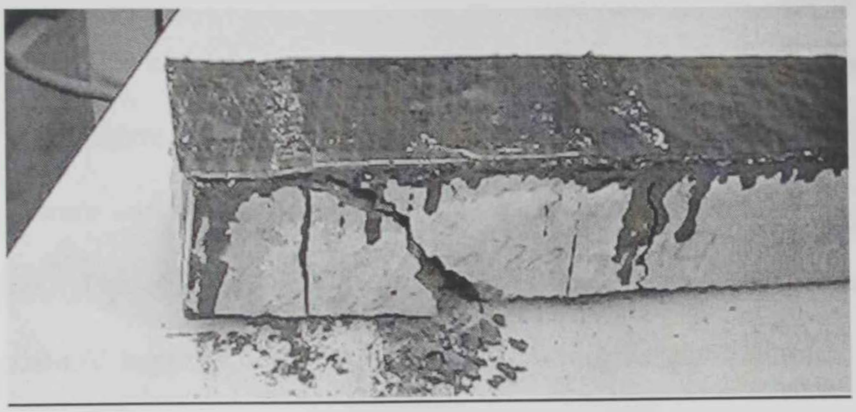


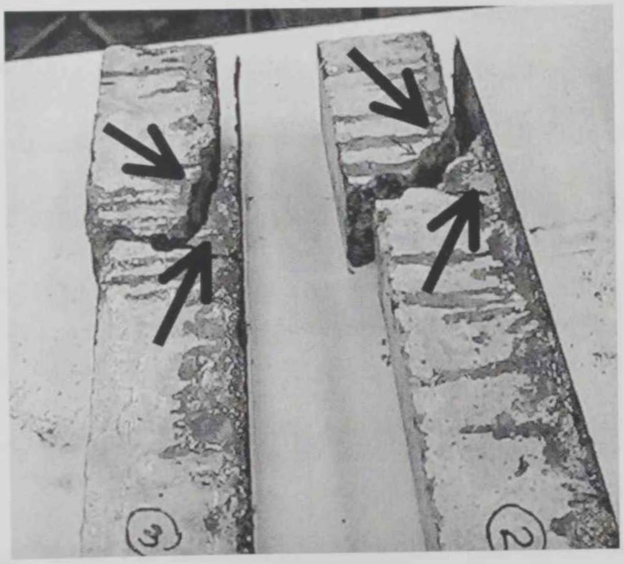
Figure (4.4): *Comparison of the average fracture load for plain concrete beams and strengthening beams by FRP*

From the failure profiles recorded according to the test of strengthened beams shown in **(Figure 4.5)**, it appears that the main failure mechanism is the de-bonding of the composite layers. This brings the issue of the interface between the composite sheet and the concrete forward. This interface which control the quality of strengthening provided by the composite laminate. It is then important to concentrate on both, surface preparation for the concrete before application and type of adhesive used, FRP de-lamination becomes a crucial consideration, especially if the sheet is not wrapped around the beam entirely.

Also it is worth mentioning that failure in the strengthened beams did not occur at the same place (**Figure 4.5-b**). It is clear that by strengthening the beam, a completely new structure is created. In conclusion, it is obvious that composite materials have a good potential for strengthening even damaged structures, also they can be used to make improvements and correction of the design's errors to increase structural integrity and strengthen historical buildings that lack sufficient reinforcing elements.



(a)



(b)

Figure (4.5): *Flexural testing of the strengthened concrete beams (a), de-bonding of the composite laminate (b) and appearance of new and propagation of existing cracks.*

4.1.2 Accelerated Degradation of FRP Laminates

Durability and long term performance of fiber reinforced composite are important research issues, especially for materials intended to be used in infrastructure and particularly in this region known for severe environmental conditions such UAE.

For that reason, materials under investigation were subject to accelerated environmental testing. Here the experiments included three types of specimens (carbon, glass and glass/aramid fibers) those tested under 3 types of tests:

1- Composite (FRP) Laminates

Two types of instruments used for the composite laminates, they are as following:

(a) Specimens were conditioned in an environmental chamber where specific conditions were prevailing. The chamber is constructed of corrosion-resistant materials enclosing eight fluorescent UV lamps, a heated water pan, and a rack for holding the test specimens. The conditions simulate the deterioration caused by sunlight and water as rain or dew according to the ASTM standard G-53. The specimens were alternatively exposed to ultraviolet light and to condensation (steam) in a repetitive cycle. The UV source was an array of fluorescent lamps, with lamps emission concentrated in the UV range. On this test the samples tested on 2 cycles, first one for 4 days under 40°C and humidity and the second cycle for 4 days under 70°C and UV light. The specimens were under this environment for a total of 2000 h, thus simulate exposure of more than 10 years under normal conditions regarding to ASTM G-53.

(b) Second experiment done for additional specimens placed in an oven, where a fully humidity saturated environment prevails. This environment was made possible by a continuous supply of distilled water, which is heated in order to bring the relative humidity to 95% and 50°C. The oven was also continuously illuminated by ten UV lamps in order to provide a continuous UV radiation. Knowing the power of the lamps and the exposed area, it was possible to compute the intensity of the radiation which was close to 250w/m^2. The test was performed for a period of six months and a weekly recording of the weight.

2- Strengthened Concrete Elements

This concrete had been caste as a "biscuits" having a square cross-section (25 x 25 mm) and a length of 150 mm. these biscuits then strengthened using the same procedure used previously for strengthening the plain concrete beams. The strengthened structural elements (biscuit) were subjected to two different types of testing as following:

(a) Exposure to high temperature and dry environment (oven)

On the dry environment, the elements placed in an oven **(Figure 4.6)** where an average temperature of oven was 50°C in order to assess the effect of this temperature on the strengthened elements. The test duration was six months.

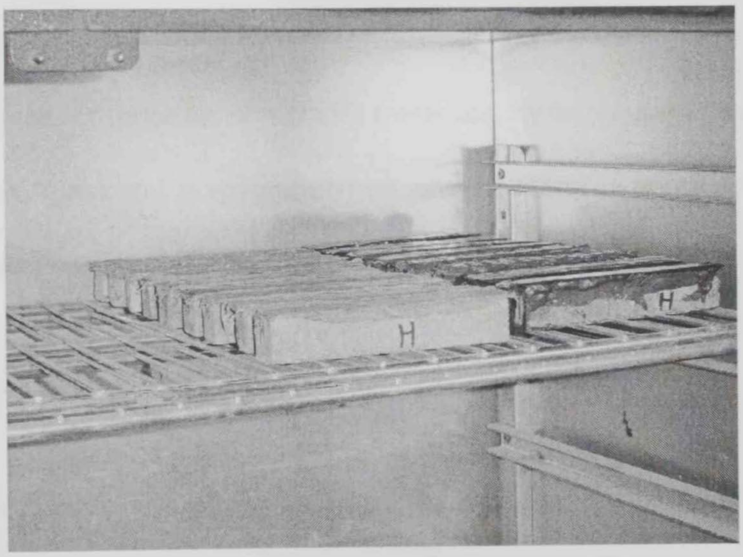


Figure (4.6): *Concrete specimens reinforced by FRP inside the oven*

(b) Exposure to high temperature and saturated environment (saturation bath).

The reinforced concrete elements were exposed to a fully saturated environment using a saturation bath device see **(Figure 4.7)**. This device contained hot water; having an average temperature approximately 50°C and humidity 90% in which the concrete elements were exposed to the water vapor. The duration of the test was same as the previous ones (six months).

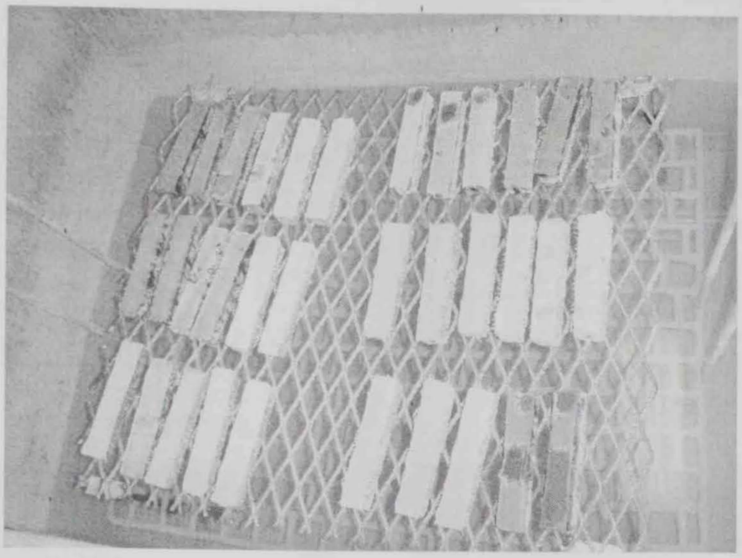


Figure (4.7): *Concrete Specimens reinforced by FRP exposed to saturated environment.*

3- Immersion composite laminates on normal water

This was the third experiment for composite materials, by immersion three laminates from each fiber (carbon, glass and glass/aramid) on normal water in room temperature for six months with weekly recording for the gain weight.

4.2 RESULTS DISCUSSION

The composite laminates were subjected to mechanical load using the three point bending test method according to ASTM standard D790 (**Figure 4.8**). Test's results for the average flexural modulus for both conditioned (environmental chamber according to-ASTM G53 and oven) and virgin specimens are shown in (**Figure 4.9**) and (**Figure 4.10**). It is worth mentioning that the obtained results were the average for five readings according to the results (**Table 4.1**) of conditioned sample under ASTM G53.

Table (4.1): *Results of three point bending test for the composite laminates*

Sample	Spcmn	D	L	width	Peak Load	%Strn @ Pk Ld	Modulus	Average Modulus	STDEV
I. D.	No.	Mm	Mm	mm	kN	%	MPa		
(Carbon Fiber, Fosroc Resin)									
Carbon	1.00	2.99	48.00	26.69	0.80	2.10	13123.90	**14775.37**	**5567.82**
	2.00	3.53	48.00	25.32	0.94	3.10	10220.10		
	3.00	2.40	48.00	26.00	0.73	1.80	20982.10		
(Glass Fiber, Fosroc Resin)									
Glass	1.00	2.98	54.00	25.06	0.71	2.60	9890.70	**8088.40**	**1580.44**
	2.00	3.49	54.00	25.22	0.76	3.00	7435.40		
	3.00	3.74	54.00	25.05	0.89	3.00	6939.10		
(Aramid Fiber, Fosroc Resin)									
Glass/Aramid	1.00	4.23	68.00	29.24	1.40	2.60	11973.90	**12099.07**	**389.54**
	2.00	4.27	68.00	25.33	1.33	2.90	11787.50		
	3.00	4.10	68.00	24.91	1.17	2.50	12535.80		

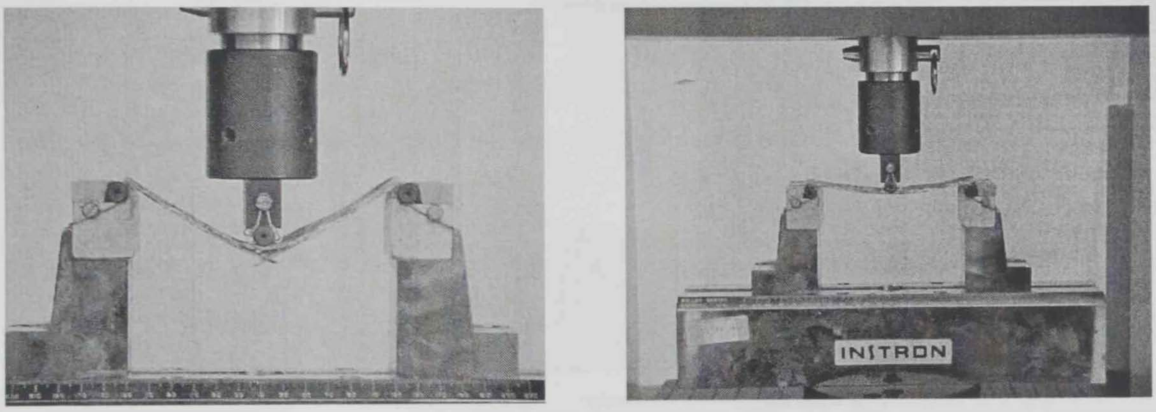


Figure (4.8): *Failure of composite laminate under three points bending test*

As long term testing exposures to both wet and dry environment combined to UV radiation, results in a decrease of the flexural modulus of the composite laminate **(Figure 4.9)**,. This reduction in the mechanical properties was common to all types of fibers. For instance, carbon composites saw its modulus decreasing from an average of 17 GPa to 14.8 GPa. Initial visual observation suggests that resin properties and the fiber/matrix interface are responsible for this degradation, but more results will be presented in the SEM section. The same trend was also observed with samples subjected to fully hot and saturated environment. The flexural modulus for all types of materials decreased except for glass/aramid specimens where the modulus after exposure show a small increase, which can be considered as being within the experimental permissible error.

Again referring to **(Figure 4.9)** and **(Figure 4.10)** reduction on strength for aramid and glass show large different between test (1) and test (2) which mean that the elevated of temperature and humidity on the second test effect extremely on the aramid and glass fibers properties. Comparing with carbon fiber, the strength and shows small different which explain that carbon less sensitivity. From above obvious, that the time is less effectively on fiber's properties than extreme weather.

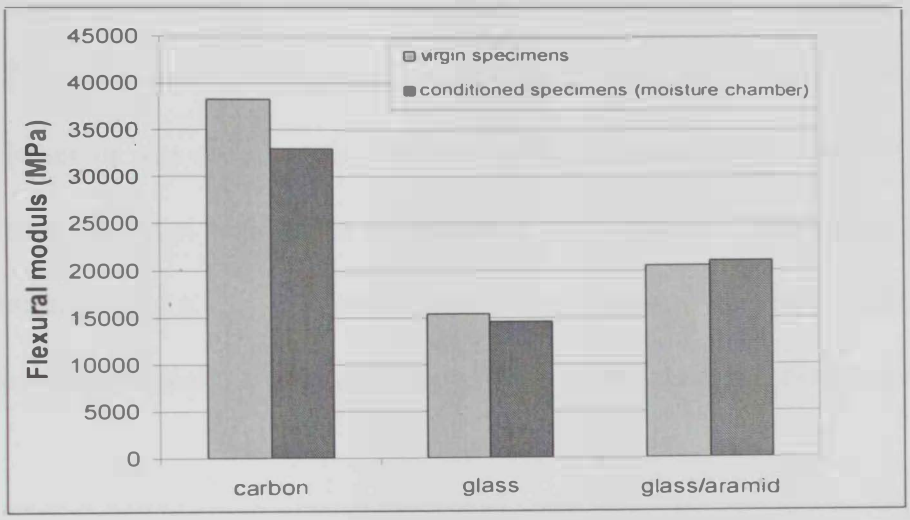


Figure (4.10): *Effect of moisture and UV radiation (oven) on flexural modulus*

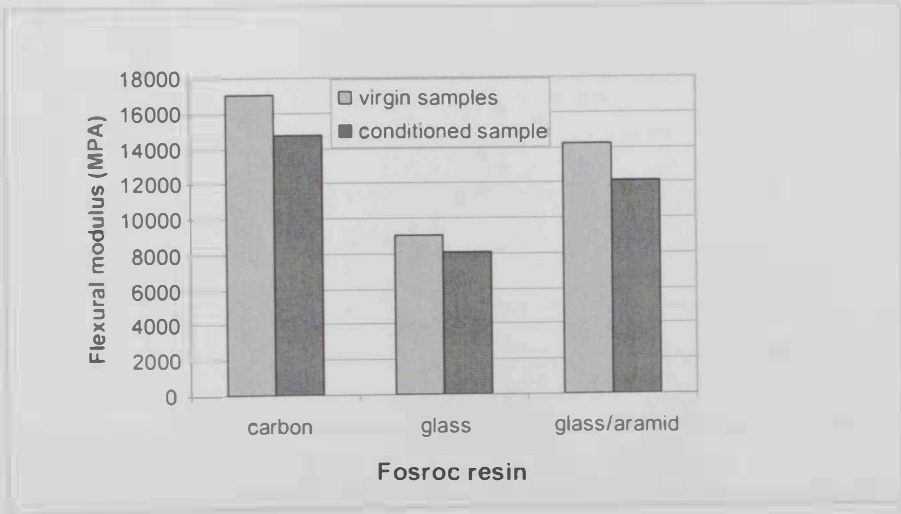


Figure (4.9): *Effect of long term conditioning (ASTM-G 53) on the flexural modulus.*

The effects of UV exposure are usually confined to the top few microns of the surface. However, in some cases, degradation at the surface of a polymeric component has been shown to affect mechanical properties disproportionately, as flaws that result from surface photo-degradation can serve as stress concentrators and initiate fracture at stress levels much lower than those for unexposed specimens. The effect of ultraviolet radiation is also compounded by the action of temperature, moisture. UV-induced damage to a polymeric material can generally be assessed either by direct visual inspection as *illustrate on the samples (aramid, glass and carbon) of loss of gloss, yellowing and flaking.*

Composite samples which, immersed in water for a period up to a sixth month, a bi-weekly recording of their weight was performed. According to the results shown in **(Figure 4.11)**, a common behavior was observed for the three different materials. Actually it is possible to identify three different regions for the moisture performance of these samples. A first region characterized by a very low water intake, then a second region where a high water intake is recorder and finally a constant region where water intake reaches saturation.

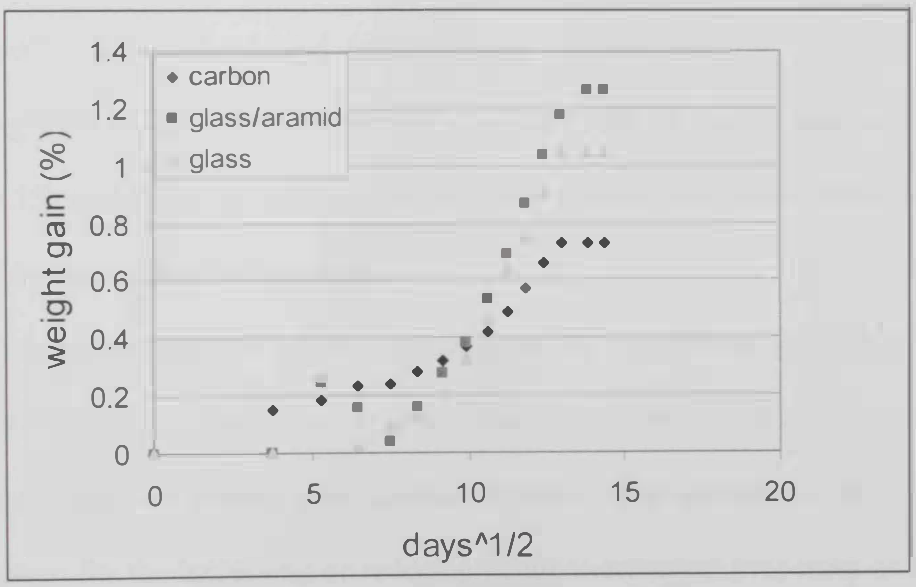


Figure (4.11): *Weight gain following complete water immersion.*

Longer immersion times resulted in lower flexural modulus for composite specimens as shown in **(Figure 4.12)**. The lowest reduction was recorded for glass/aramid specimens. Fiber impregnation and the quality of the fiber matrix interface are the determining factors for the performance of these materials.

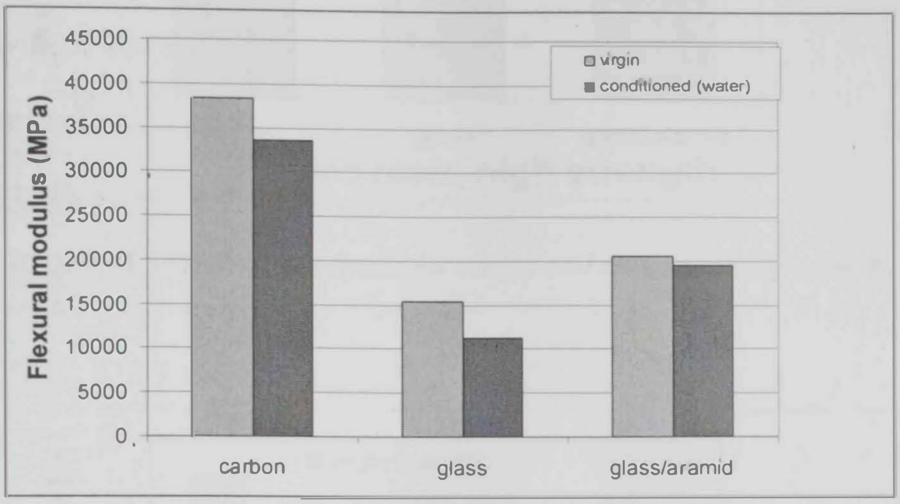


Figure (4.12): *Effect of water immersion on the flexural strength.*

Concrete biscuits reinforced with composites which exposed to hot and dry environment were also tested using a three point bending test. Here, only the maximum fracture load was recorded. Both normal and high strength concrete biscuits were used. Again conditioning for a longer time will affect the performance of these materials as shown in **(Figures 4.13)** and **(Figure 4.14)** except for glass/aramid specimens where conditioned specimens showed higher fracture loads.

That refers to more than one reason regarding to the complicated circumstances of the concrete/FRP system started from type of fiber culminated to the interface between concrete and composite including the interface between fiber and matrix, the materials not the only reason for the increasing or reducing of the mechanical properties of the system. Quality of work, application and surface preparation also main issues control the properties of the strengthening system.

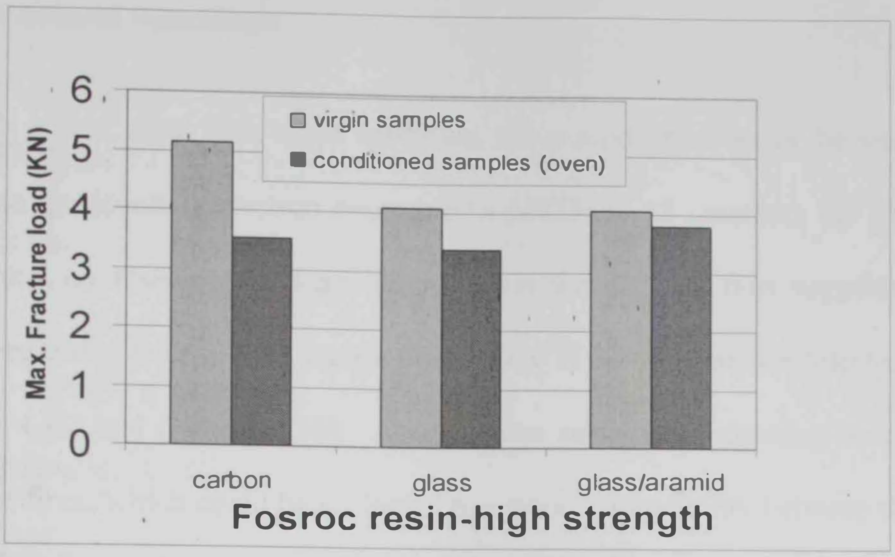


Figure (4.13): *Fracture loads for virgin and conditioned specimens*

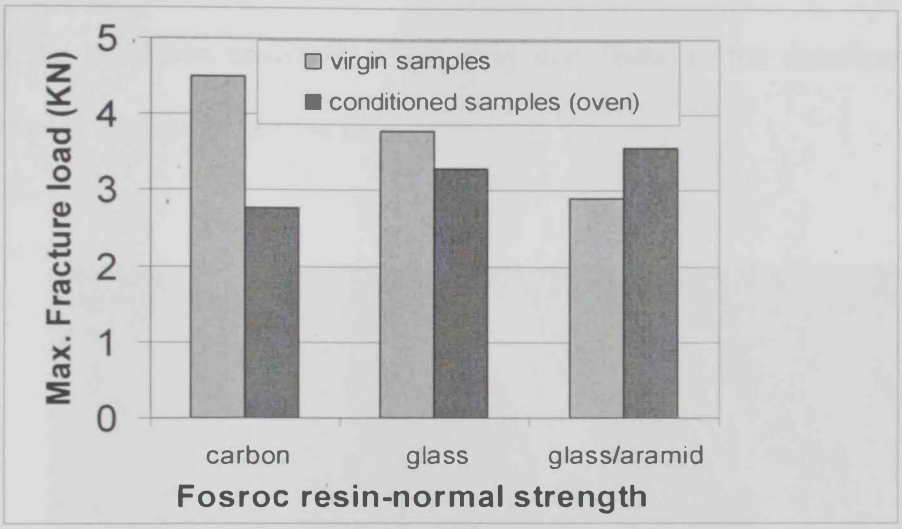


Figure (4.14): *Fracture loads for virgin and conditioned specimens (Normal strength concrete)*

4.3 CHARACTERIZATION OF FRACTURED SURFACES (SEM)

Specimens that were subject to environmental conditioning under **ASTM G53** experiment, were tested under three point flexural bending test and the fractured surfaces were analyzed using the scanning electron microscope. Fractured surfaces of virgin samples were also analyzed for benchmarking.

4.3.1 Glass/Aramid Specimens

The analysis is concerned with virgin specimen, the aramid fibers are in the weft direction. According to the scanning electron micrographs *(ASTM G-53 samples)*, the fibers surface was clean and no resin debris were identified on the surface, thus suggesting that the failure was resulting mainly from matrix de-bonding at the fiber-matrix interface as shown in **(Figures 4.15)** and **(Figure 4.16)**. Also one can see, some loosening occurring at the origin of the fiber, which could be attributed to a poor compatibility between the fiber and the matrix being used. According to these observations see **(Figure 4.17)**, it is important to develop better coupling and surface treatment methods in order to enhance the adhesion between the fiber and the matrix. There was no evidence of poor wetting or the occurrence of voids in the specimen analyzed, which may contribute in the deterioration of the interface between the matrix and the fiber.

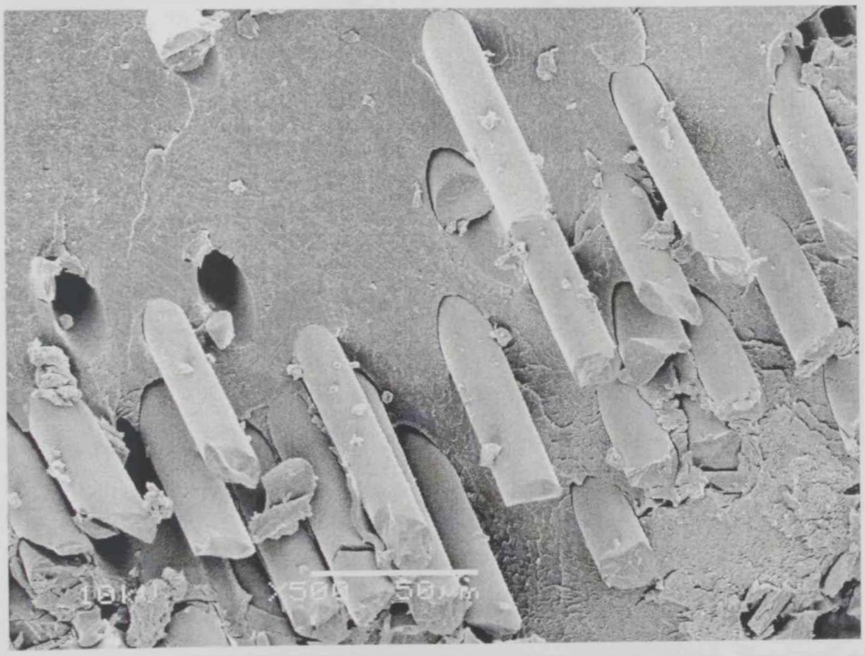


Figure (4.15): *SEM of fractured glass/aramid specimen (virgin).*

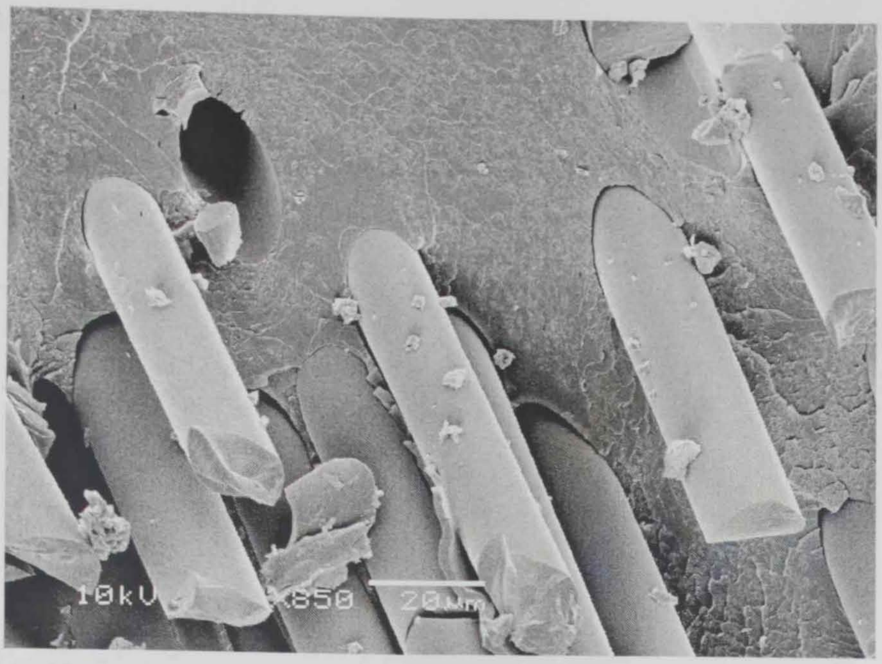


Figure (4.16): *Enhanced magnification showing clean glass/aramid fibers surface and some loosening at the fiber origin (virgin).*

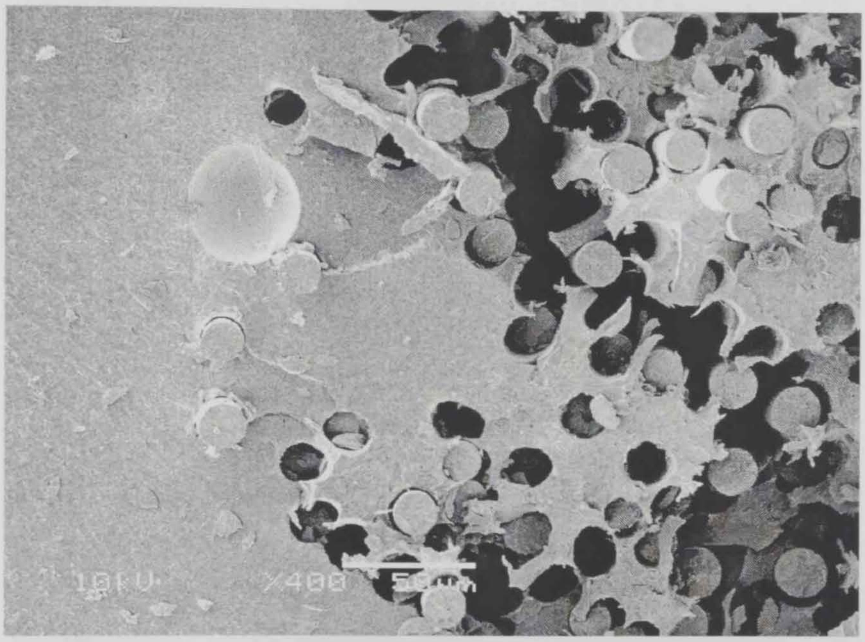


Figure (4.17): *Fibers pull-out which may be originating from a poor compatibility between the glass/aramid fibers and the matrix (virgin).*

Similar specimen surfaces that were subject to environmental then flexural testing were also analyzed using the scanning electron microscope. Failure was also resulting from a matrix-fiber de-bonding at the fiber-matrix interface. From the scanning electron micrographs pictures shown in **(Figures 4.18)** and **(Figure 4.19)**, it is clear that there was a large gap surrounding the fiber, it looks like some yielding of the matrix occurred. It seems that the testing temperature was close to the glass transition temperature of the resin (T_g).

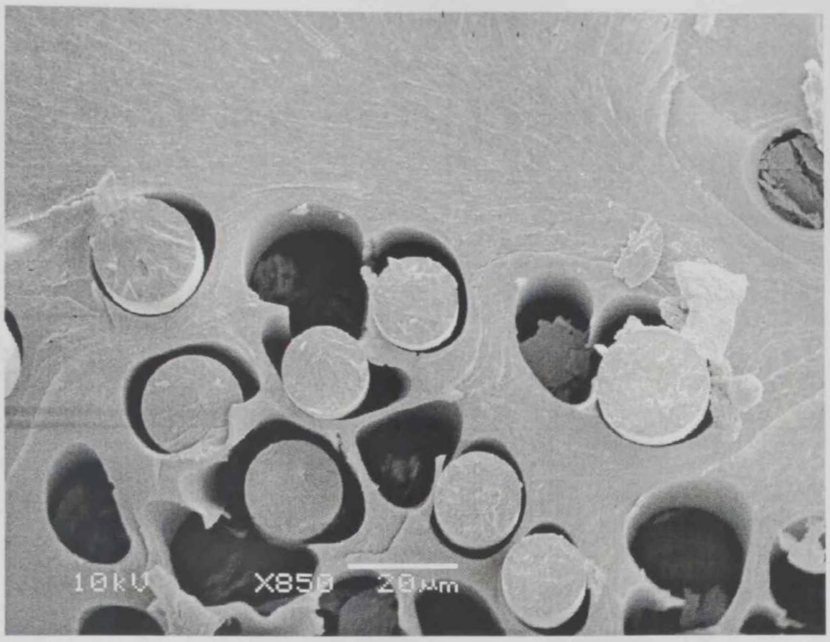


Figure (4.18): *Enhanced magnification showing large gap surrounding the glass/aramid fibers (conditioned).*

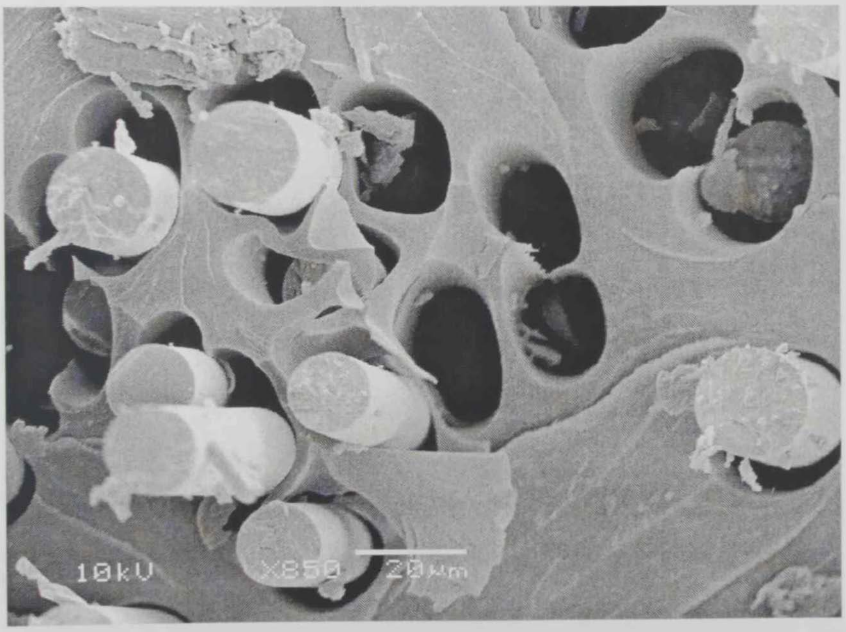


Figure (4.19): *Enhanced magnification showing complete de-bonding between the fibers and the matrix.*

4.3.2 Carbon specimens

For the virgin specimens, failure occurs mostly through matrix cracking and de-lamination as shown in the scanning electron micrographs depicted in **(Figures 4.20)** and **(Figure 4.21)**. Fibers and matrix are exhibiting a strong bond.

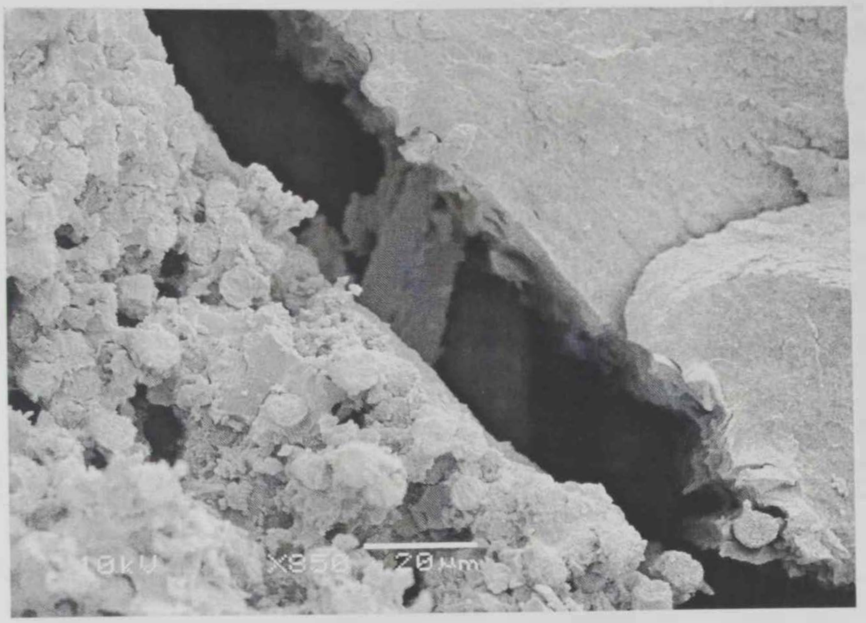


Figure (4.20): *Carbn fiber specimen failure resulting from matrix cracking (virgin).*

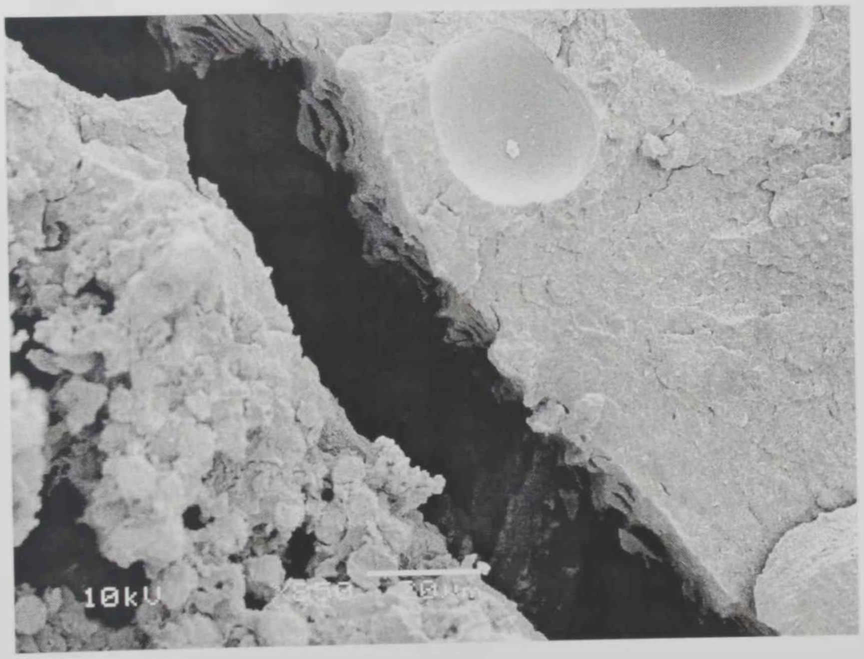


Figure (4.21): *Enhanced magnification showing matrix cracking and good adhesion between the carbon fibers and the matrix (virgin).*

For the specimens subjected to environmental testing, the failure was resulting from a matrix fiber de-bonding rather than matrix cracking as it was observed for the virgin specimens. It looks like the high temperature that was prevailing during conditioning and its long duration causes the matrix to yield, see **(Figures 4.22)** and **(Figure 4.23)**.

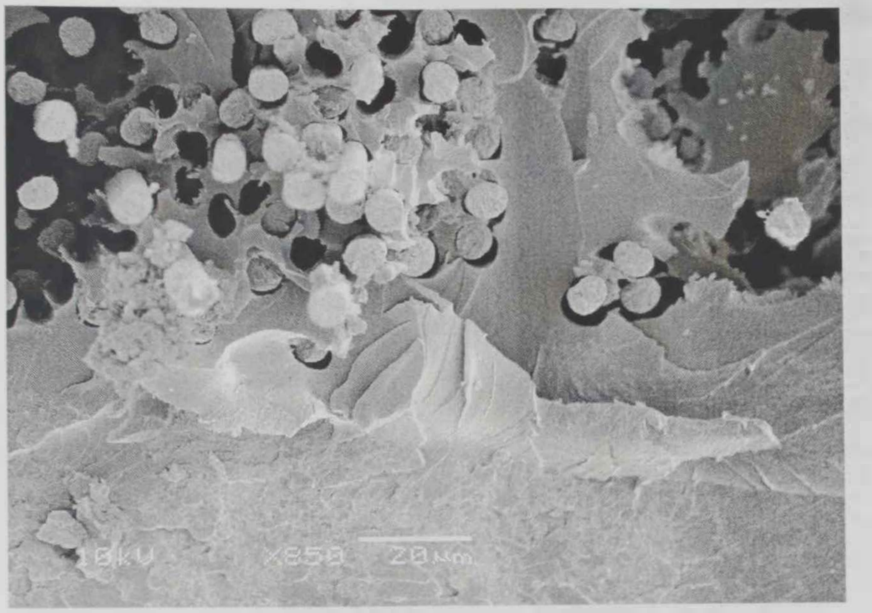


Figure (4.22): *Enhanced magnification showing de-bonding between the CFRP / matrix.*

Figure (4.23): *Enhanced magnification showing large gaps Surrounding the carbon fibers.*

4.3.3 Glass specimens

For virgin specimens, failure occurs as a consequence of the poor interface between the fiber and the matrix. It is important to enhance the fiber surface properties through better surface treatment in order to increase the adhesion between the fiber and the matrix see **(Figures 4.24)** and **(Figure 4.25)**.

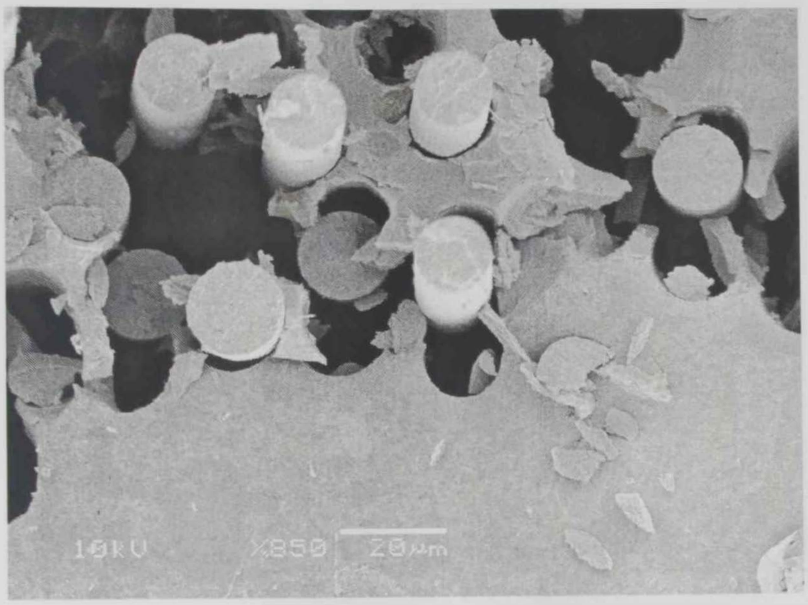


Figure (4.24): *Failure was resulting from a poor compatibility between glass fibers and the matrix (virgin).*

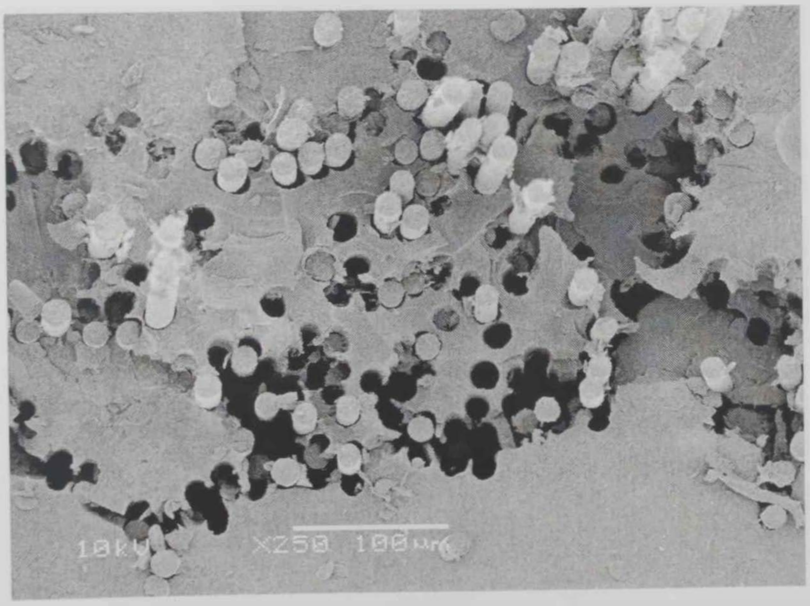


Figure (4.25): *Poor adhesion between glass fibers and matrix as evidenced by SEM.*

For the conditioned specimens, failure occurs also as a result of matrix de-bonding as shown in **(Figures 4.26)** and **(Figure 4.27)**. Longer conditioning time combined to high temperature and moisture is causing the matrix to yield, which is resulting in a complete separation between the matrix and the fiber as it is shown through the relatively large gap that surrounds the fiber.

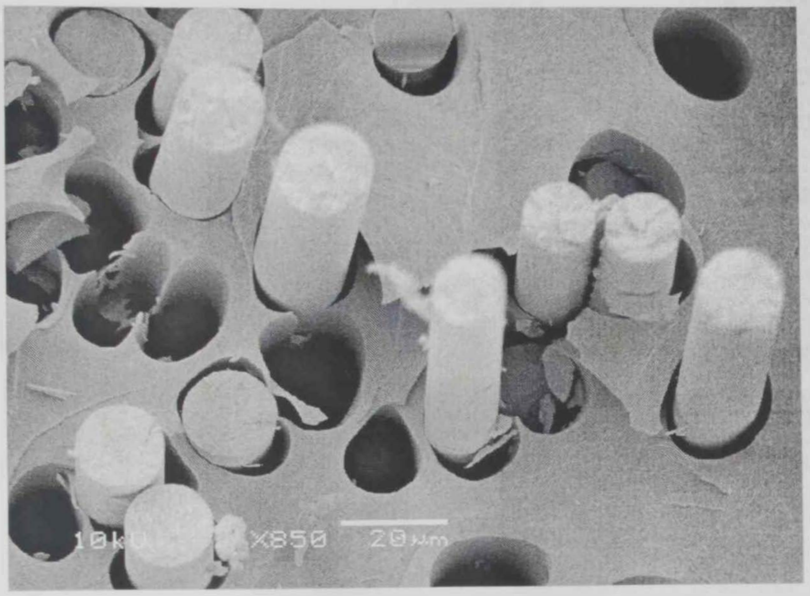


Figure (4.26): *Enhanced magnification showing clean glass fibers surface and large gaps surrounding the fibers at their origin.*

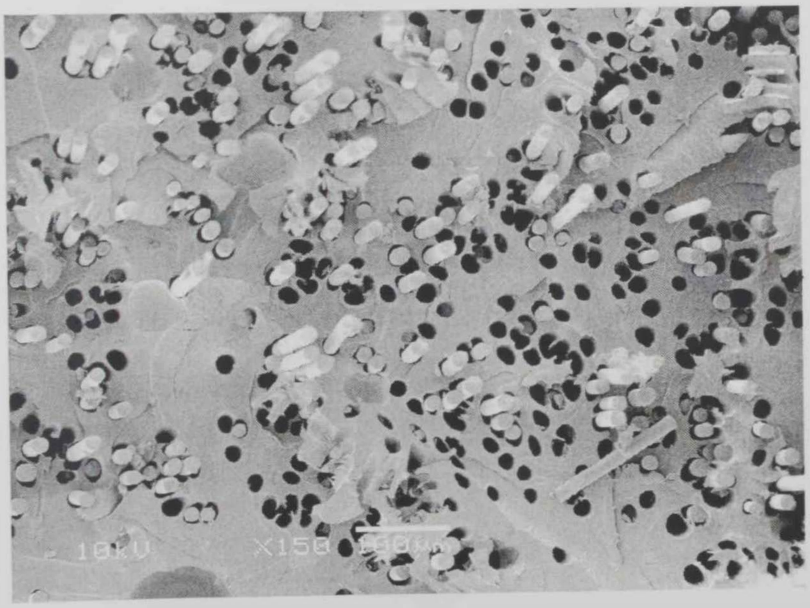


Figure (4.27): *Poor adhesion between glass fibers and matrix resulting in complete de-bonding of the fibers.*

Chapter -5-

Chapter 5

Conclusion and Recommendations

This work investigates the durability and performance of FRP materials when exposed to environmental degradation. It is widely acknowledged that the prediction of the durability of composite systems under mechanical and environment loading is greatly complicated by the occurrence of several interaction physico-chemical and mechanical degradation mechanisms. Our interest, in particular, was in demonstrating the potential of using composite materials in comparison to reinforce plain concrete structures, considering both, if reinforcement steel as a constant value and if the damage will be noted before reaching to the reinforcement of structures. Also, given the severe climatic conditions prevailing in the region like high temperature, humidity and UV, it was interesting to investigate the durability and the long-term performance of these materials when subject to these extreme conditions in the labs for the FRP materials and concrete/FRP structures. Although the duration of exposure can't be classified as a long term exposure, it was possible to obtain some results by accelerating the degradation process.

Specimens were divided into different groups that were subjected to different exposure times and immersion in water, then testing was performed using a three point bending test. Results of conditioned specimens were compared to virgin specimens to assess the extent of composite degradation.

According to the experimental results performed either on actual concrete beams or on a lab scale, composite materials offer a very interesting alternative as a repair and strengthening materials. For instance, it was demonstrated that even for the case of non-reinforced structures, these materials are bringing back their structural integrity. This is very important, if we know that there is a real concern here regarding the restoration of historical buildings, which are often executed with traditional materials, which can not support the ordinary regular conventional methods for repair.

For the durability of the repaired structures, initial results suggest that exposure for longer time under the severe climatic conditions prevailing here may affect the performance of the materials. these facts may be explained due to the knowledge that these materials were initially developed for countries with different climatic conditions. however, the reduction of the properties wasn't large according to the simulated conditions.

After reviewing the SEM (Scanning Electron Microscopy) images of fractured specimens, analysis suggests that poor compatibility between the fiber and the matrix is responsible for the reduction in the mechanical properties of these composites. Also, resin properties were also affected by longer conditioning times. Specimens exposed to high temperatures and fully saturated environments were subject to degradation caused by water diffusion through the matrix. Obviously, longer exposure periods would accelerate the initiation and propagation micro-crack present ate the surface, thus contributing to diffusion process taking place within the matrix.

Actually, visual observation of the specimens showed a discoloration of the composite especially glass/aramid fiber that changed to light yellow, which could be interpreted as resulting from further fiber cross linking exposed to UV. Accordingly it is important to address these issues in order to enhance the performance of these materials. Special resin formulations exhibiting higher glass transition temperature should be formulated. Also better surface treatment methods for the fibers should be developed in order to enhance the adhesion between the fibers and the matrix. It was difficult to assess the effects of UV alone due to the fact that most studies were carried out in an outdoor environment or in an artificial weathering device where moisture was also present. The most deleterious effects of UV exposure are probably not due to the actual UV damage, which is limited to the surface, but to the potential for increased moisture ingress in the damaged regions.

Results of testing in outdoor environments are seldom reproducible, due to the highly variable nature of the weather and associated climactic factors. Thus, tests carried out on the same material are difficult to compare even if they were conducted at the same site and time of year. There are also a number of systematic errors associated with current commercial laboratory weathering devices which make it difficult to compare results between nominally identical test devices, and even within the same device. At best, the current testing methodology can be used to compare unknown materials to a reference material within a particular test run, or to rank materials within a particular test run.

REFERENCES

1. S, Al-Bahar & E, Attiogbe, "Corrosion Induce Deterioration Of Reinforced Concrete Structures In Kuwait", Paper Titled Proceedings Of CONSEC' 95, Sapporo Japan, Pp. 565-573

2. Mike Walker, "Reinforced Concrete In The Environmental Conditions Of The Arabian Peninsula- Including Basic Needs And Consideration For Satisfactory Performance And Philosophy And Use Of Whole Life Costing", conference on Deterioration of reinforced concrete in the Gulf and methods of repair, 15-17 December 1996, Muscat, Sultanate of Oman.

3. Steen Rostam, "Assessment and repair strategies for damaged structures", conference on Deterioration of reinforced concrete in the Gulf and methods of repair, 15-17 December 1996, Muscat, Sultanate of Oman

4. ACI Committee 201, "Guide To Durable Concrete", ACI 201.2R-92

5. PCA Portland Cement Association, 2002, " Types And Causes Of Concrete Deterioration", Concrete Information

6. Ted Kay and Mike Walker, "Guide to evaluation and repair of concrete structure in the Arabian Peninsula", published by the concrete society in collaboration with the Bahrain society of engineers, 2000

7. Brosens K., Ahmed O, Van Gemert D. and Ignoul S., "Strengthening of R.C. Beams - Hybrid steel/CFRP solutions", Structural Faults & Repair 99, 8th International conference, 13-15 July 1999, London, England

8. P.K. Mallick, "Fiber-Reinforced Composites, Materials, Manufacturing And Design", Second Edition, Revised And Expanded, USA, 1993

9. Benjamin Tang, "Fiber Reinforced Polymer Composites Applications In USA Dot", Published In Korea/U.S.A. Road Workshop Proceedings, January 28-29, 1997

10. V.M. Karbhari, "Chapter 1: Introduction, Gap Analysis For Durability Of Fiber Reinforced Polymer Composites In Civil Infrastructure", by CERF (Civil Engineering Research Foundation), 2001 by the American Society of Civil Engineers

11. D. Hunston, T. Juska, V.M. Karbhari, R. Morgan, C. Williams, "Chapter 3: Effects of Moisture/Aqueous Solutions", Gap Analysis For Durability Of Fiber Reinforced Polymer Composites In Civil Infrastructure, by CERF (Civil Engineering Research Foundation), 2001 by the American Society of Civil Engineers

12. B. Benmokrane, S. Faza, H.V.S. GangaRao, V.M. Karbhari, M. Porter, "Chapter 4: Effects of Alkaline Environment", Gap Analysis For Durability Of Fiber Reinforced Polymer Composites In Civil Infrastructure, by CERF (Civil Engineering Research Foundation), 2001 by the American Society of Civil Engineers

13. U.S. Army Corps of Engineers, Chapter 6: Durability, (1997) Durability. In: "Composite Materials for Civil Engineering Structures". Engineer Technical Letter, ETL 1110-2-548, 31 Mar 97

14. T. Juska, P. Dutta, L. Carlson, J. Weitsman, "Chapter 5: Thermal Effects", Gap Analysis For Durability Of Fiber Reinforced Polymer Composites In Civil Infrastructure, by CERF (Civil Engineering Research Foundation), 2001 by the American Society of Civil Engineers

15. J.W. Chin, J. Martin, T. Nguyen, "Chapter 8: Effects of Ultraviolet (UV) Radiation", Gap Analysis For Durability Of Fiber Reinforced Polymer Composites In Civil Infrastructure, by CERF (Civil Engineering Research Foundation), 2001 by the American Society of Civil Engineers

16. Nanni, A, "Composites: Coming on Strong", Concrete Construction Journal, vol. 44, (1999), p. 120

17. Kin-Tak Lau, Li-Min Zhou, Ping-Cheung Tse and Li-Bo Yuan, "Applications of composites, Optical Fiber Sensors and Smart Composites for Concrete

Rehabilitation: An Overview", Applied Composite Materials Journal, Vol.9, P. 221-247, 2002

18. Khalifa, A., W.J. Gold, A. Nanni, and M.I. Abdel Aziz, "Contribution of Externally Bonded FRP to Shear Capacity of Flexural Members", ASCE-Journal of Composites for Construction, Vol. 2, No.4, Nov. 1998, pp. 195- 203

19. Leming, M.B. and Peshkam, L.G.,"Structural Faults and Repairs", Proceedings of the Sixth International Conference Pp. 161-162. 1995

20. Houssam Toutaanji, Gerardo Ortiz, "The Effect Of Surface Preparation On The Bond Interface Between FRP Sheets And Concrete Members", Composite Structures 53 (2001) 457-462

21. Oral Buyukozturk, Oguz Gunes, Erdem Karaca, "Characterization And Modeling Of De-bonding In RC Beams Strengthened With FRP Composites", 15th ASCE Engineering Mechanics Conference June 2-5, 2002, New York

22. J.G. Teng, S.T. Smith, J. Yao, J.F. Chen, "Intermediate Crack-Induced De-bonding In RC Beams And Slabs", Construction And Building Materials Journal, Vol. 17, Pp. 447--462, 2003

23. Concrete Society, "Design Guidance For Strengthening Concrete Structures Using Fiber Composite Materials", Technical Report No. 55, Report Of A Concrete Society Committee, 2000

24. Tumialan, G., Serra, P., Nanni, A. and Belarbi, A., "Concrete Cover De-lamination in RC Beams Strengthened with FRP Sheets," SP-188, American Concrete Institute, Proc., 4th International Symposium on FRP for Reinforcement of Concrete Structures (FRPRCS4), Baltimore, MD, Nov. 1999, pp. 725-735

25. Arduini, M., A. Di Tommaso, And A. Nanni, "Brittle Failure In FRP Plate And Sheet Bonded Beams", ACI Structural Journal, Vol. 94, No. 4, July-Aug. 1997, Pp. 363-370

26. Malek, A., Saadatmanesh, H., And Ehsani, M. "Prediction Of Failure Load Of R/C Beams Strengthened With FRF Plate Due To Stress Concentrations At The Plate End", Structural Journal, American Concrete Institute, Vol. 95, No. 1, January-February 1998, Pp. 142-152

27. Lamanna, A.J., Bank, L.C., and Scott, D.W., "Rapid Strengthening of RC Beams using Powder Actuated Fasteners and FRP Strips", in Proceedings of the 5th International Symposium of FRP in Reinforced Concrete Structures, Cambridge, UK, pp. 389-397, July 16-18 2001

28. Lamanna, A.J., Bank, L.C., and Scott, D.W., "Flexural Strengthening of RC Beams using Fasteners and FRP Strips", ACI Structures Journal, Vol. 98, No. 3, pp. 368-376, 2001

29. Spadea, G., Bencardino, F., and Swamy, R. N., "Structural Behavior of Composite RC Beams with Externally Bonded CFRP", ASCE Journal of Composites for Construction, Vol. 2, No. 3, pp. 132-137, August 1998

30. Khalifa, A., T. Alkhrdaji, A. Nanni, and S. Lansburg, "Anchorage of Surface Mounted FRP Reinforcement", Concrete International: Design and Construction, Vol. 21, No.10, Oct. 1999, pp. 49-54

31. Kasumassa Nakaba, Toshiyuki Kanakubo, Tomoki Furuta, And Hiroyuki Yoshizawa, "Bond Behavior Between Fiber-Reinforced Polymer laminates And Concrete", ACI Structura Journal, Technical Paper, Title No. 98-S34

32. Karbhari, V. And Howie, I., "Effect Of Composite Wrap Architecture On Strengthening Of Concrete Due To Confinement: Ii-Strain And Damage Effects", Journal Of Reinforced Plastics And Composites, Vol. 16, 1997

33. U.S. Army Corps of Engineers, "Chapter 9: Repair Of FRP Composites", Durability. In: Composite Materials for Civil Engineering Structures. Engineer Technical Letter, ETL 1110-2-548, 31 Mar 97

إعادة تأهيل المباني الخرسانية
باستخدام المواد المركبة

مقدمة

في دراسات سابقة للمنشات الخرسانية في دول منطقة الخليج أظهرت النتائج مؤشرا خطيرا للعمر الافتراضي للمباني، حيث حددت 10-15 سنة هو العمر المتوقع لبقاء المبني صالحا للاستخدام بدون الحاجة إلى صيانة جذرية.

تعتبر طرق الصيانة التقليدية، ذات عمر افتراضي وحماية محدودة و مؤقتة، لذا يرى ذوي الاختصاص في المنطقة إن الحاجة لصيانة المباني سوف تزداد بمرور الوقت مما يترتب عليه زيادة في المخصصات المالية لأعمال الصيانة والتي تزداد تكلفتها بزيادة عمر المبنى وبزيادة استخدام نفس الطرق و المواد التقليدية للصيانة.

لذلك وبسبب الحاجة الملحة لعمليات الصيانة المتزايدة بسبب المناخ العام للمنطقة ومناخ دولة الإمارات بشكل خاص دعت الحاجة للتفكير بطرق حديثة لصيانة المباني لتعطيها عمر افتراضي أطول و تكون قادرة على التأقلم ومقاومة ظروف الطقس للدولة ودول المنطقة والذي يتسم بدرجة حرارة ورطوبة عالية، بحيث تكون هذه الطرق الحديثة قادرة على زيادة قوة المبنى لتحمل الأحمال الزائدة في حالة تغيير الاستخدام أو زيادة الأحمال على المبنى (خاصة في الجسور ومواقف السيارات).

إن استخدام المواد المركبة (composite materials-FRP) واحدة من الحلول الحديثة والمكملة لعمليات الصيانة التقليدية، وترجع أهمية هذه المواد إلى الخواص الفريدة من حيث مقاومتها للصدأ و خفة وزنها والخواص الميكانيكية التي تماثل وربما تفوق خواص الحديد، غير أن استخدام المواد المركبة لا يغني عن الطرق التقليدية ولكن يحسنها و يزيد من فعاليتها.

في هذه الإطروحة، استخدمنا المواد المركبة في صيانة عمود خرساني غير مسلح بالمختبر لدراسة قدرة المواد الجديدة على تقوية واعادة تأهيل المباني في الواقع. بعد ذلك قمنا باختبار المواد المركبة منفردة ومع الخرسانة الغير مسلحة وذلك بتعريضها لدرجات حرارة ورطوبة عالية تحت الأشعة فوق البنفسجية بدرجة تفوق الطقس الخارجي وبشكل متواصل للإسراع في عملية التآكل للمواد المركبة ومنه معرفة قدرتها على التحمل والتأقلم في مناخ المنطقة بشكل عام وطقس دولة الإمارات بشكل خاص.

جامعة الإمارات العربية المتحدة
عمادة الدراسات العليا
برنامج ماجستير علوم وهندسة المواد

إعادة تأهيل المباني الخرسانية باستخدام المواد المركبة

رسالة مقدمة من الطالبة:

ابتسام جعفر سعيد السيفي

الى جامعة الإمارات العربية المتحدة
استكمالا لمتطلبات الحصول على درجة الماجستير في علوم وهندسة المواد

بإشراف:

د. خليل الحوسني
قسم الهندسة المدنية
جامعة الإمارات العربية المتحدة

د. عادل حمامي
قسم الهندسة الميكانيكية
جامعة الإمارات العربية المتحدة

2004

Shrieen
Digitally signed by Shrieen
DN: cn=Shrieen, o=UAE University, ou=UAEU Libraries Deanship, email=shrieen@uaeu.ac.ae, c=US
Date: 2016.09.20 16:39:55 +02'00'