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MINISTRY OF HOUSING, UTILITIES
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HOUSING AND BUILDING NATIONAL
Chapter 1 RESEARCH CENTER

EGYPTIAN CODE OF PRACTICE

FOR

THE USE OF FIBER REINFORCED POLYMER (FRP) IN THE CONSTRUCTION FIELDS

CODE NO. ECP 208-2005

EGYPTIAN STANDING CODE COMMITTEE
FOR
THE USE OF FIBER REINFORCED POLYMER (FRP)
IN THE CONSTRUCTION FIELDS
2005

THIS DOCUMENT IS THE OFFICIAL TRANSLATION OF THE FORMALIZED “**EGYPTIAN CODE FOR THE USE OF FIBER REINFORCED POLYMER IN THE CONSTRUCTION FIELDS**”.

THE ORIGINAL DOCUMENT OF THE FORMALIZED CODE IS WRITTEN IN ARABIC LANGUAGE, WHICH IS CONSIDERED TO BE THE OFFICIAL VERSION OF THE CODE,

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THE OFFICIAL TRANSLATION OF THE CODE WAS CARRIED OUT BY MEMBERS OF THE EGYPTIAN FRP STANDING CODE COMMITTEE, AND IN PARTICULAR BY MEMBERS OF THE DRAFTING AND REVIEW COMMITTEE OF THE CODE.

THE ENGLISH TRANSLATION OF THE CODE WAS TECHNICALLY REVIEWED AND EDITED BY THE CHAIRMAN AND BY THE DIRECTOR OF THE EGYPTIAN FRP STANDING CODE COMMITTEE **PROF. DR. ABDELHADI HOSNY AND PROF. DR. IBRAHIM MAHFOUZ,** RESPECTIVELY, AND WAS APPROVED BY THE EGYPTIAN FRP STANDING CODE COMMITTEE

INTRODUCTION

The advent of FRP composite technology to the industrial world dates back to the early 1940's. The early applications were limited to the aerospace and aeronautical industries that capitalized on the high-strength-to-weight-ratio capability, resistance to corrosive effects and other inherent superior properties of FRP composite materials.

FRP composites were first incorporated into the construction fields in the mid 1970's. Owing to their rapidly growing development, FRP technology is now considered to be the ideal technology to use in a number of civil engineering applications. It is noted that the current FRP technology is considered to be an emerging technology. It can, therefore, be stated that the full potentials of such advanced technology have not been fully utilized.

In Egypt, the use of Fiber Reinforced Polymer, (FRP) in the construction fields has grown rapidly and in particular for the applications involving the repair and strengthening of structures. In April 2002, the Egyptian Minister of Housing, Utilities and Development, issued a ministerial decree No.100 to establish the first Egyptian FRP Standing Code Committee. Accordingly, Egypt has taken a leading role in the formal and professional utilization of the FRP technology in the construction fields not only in the Middle East but also worldwide.

The applications included in the Egyptian code are limited only to;

a- Strengthening and Repair of concrete structures using externally bonded FRP sheets and laminates,

b- Reinforcing flexural concrete elements using FRP rods.

- **Contents of the Code:**

The code comprises the following Chapters:

Chapter 1: Scope, Principles, and Design Fundamentals

Chapter 2: Properties of fiber Reinforced Polymer Composite Materials

Chapter 3: Durability of FRP Systems

Chapter 4: Repair and Strengthening of Reinforced Concrete Structures Using Fiber Reinforced Polymer, (FRP)

Chapter 5: Concrete Structures Reinforced with FRP Bars

It is planned in the future to expand the scope of the code to include applications involving strengthening of masonry structures, prestressed concrete structures, and steel structures, as well as to the applications of Pultruded FRP precured elements in construction fields.

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CHAPTER 1

SCOPE, PRINCIPLES, AND DESIGN FUNDAMENTALS

1.1 FIBER REINFORCED POLYMER COMPOSITES, (FRP)

1.1.1 FRP SYSTEMS

Composite materials made of fibers in Polymeric resin, known as Fiber Reinforced Polymers (FRP) have emerged as an alternative to traditional construction materials. Owing to their superior properties, such as lightweight, non-corrosive, high strength and ease of installation, FRP materials and systems have been recognized and utilized in numerous construction applications. FRP composite systems consist of fiber impregnated with a saturating resin on-site, as well as, FRP composites manufactured in a wide variety of shapes off-site. The types of continuous fibers most commonly used in the construction field applications are:

A- Carbon Fibers
B- Glass Fibers
C- Aramid Fibers

The fibers give the FRP system its strength and stiffness.

A wide range of polymeric resins are used with FRP systems as primers, putty fillers, saturants and adhesives. The most commonly used resins in FRP works in the construction fields are epoxy and polyester resins.

FRP systems shall be designed to resist tensile forces only. Consequently, FRP systems shall not be relied upon to resist compressive forces. It is acceptable, however, for FRP tension reinforcement to experience compression due to moment reversals or changes in load pattern. However, the compressive strength of the FRP reinforcement shall be neglected.

FRP systems come in a variety of forms, including dry sheets impregnated with saturating resin on-site and precured systems which are manufactured of site in the following forms:

1- FRP laminates
2- FRP bars
3- Prestressing FRP tendons and strips
4- Pultruded FRP structural shapes

The use of FRP systems is governed by a number of considerations related to design requirements, acceptance criteria of FRP materials, and the nature and scopes of application in the construction fields, as given in section 1-1-2.

1.1.2 Scope of Application of FRP Composites in the Structural Engineering Fields

1.1.2.1 Strengthening and Repair of Structures (Concrete, Masonry & Steel)

FRP materials are used in the strengthening and repair of structures, as follows:

1- Externally Bonded Applications using Unidirectional or Multidirectional Dry Fiber FRP Sheets or Fabrics Impregnated with a Saturating Resin On-Site:

The system is known as wet lay-up FRP system in which the saturating resin, along with the compatible primer and putty is used to bond the FRP sheets to the concrete surface. The system can be used in strengthening structural elements having flat surfaces such as beams and slabs. The dry fiber FRP sheets can also be wrapped after impregnation with the polymer resin to conform to the geometry of structural elements having non-flat surfaces such as columns. The relatively thin profiles of cured FRP systems are often desirable in applications where aesthetics or access is a concern.

2- Precured FRP Units Manufactured off-Site:

The precured FRP manufactured units used in strengthening and repairing of concrete structures can be carried out in one of the following ways:

a- Externally bonded applications involving FRP composite laminated strips bonded to the concrete surface using adhesive along with the primer and putty.
b- Near surface Mounted Laminated strips in which the strips are inserted inside slits cut into the concrete cover and bonded to the concrete into the slits
c- Near Surface Mounted FRP bars in which the bars are inserted inside slits made in the concrete cover and bonded to the concrete into the slits
d- Pultruded FRP Structural shapes connected to the concrete unit using dowels and/or adhesive along with the primer and putty.
e- External prestressing of concrete structures using Prestressing FRP tendons and strips.
f- The preceding methods of strengthening and repair of structures can either be used separately or in combination thereof.

Such units cannot be bent once it has been manufactured. Thus, they cannot be reshaped on-site

1.1.2.2 Concrete and Masonry Structures Reinforced with FRP Bars & Prestressed Concrete Structures Using FRP Tendons**:**

FRP bars can be used as reinforcement for concrete and masonry structures. FRP tendons and can also be used for the internal and external prestressing of concrete elements.

1.1.2.3 The Use of Pultruded FRP Structural Shapes as Structural Units:

Pultruded FRP structural shapes are ideally suited for the use in the construction of certain types of new structures. These structures include but are not limited to light weight structures and structures subjected to aggressive environmental exposures. For such applications the light-weight and non-corrosive properties of FRP composites can be utilized to advantage.

1.2 SCOPE OF THE CODE

1- The scope of the code are limited only to the following two types of applications :

   a- Strengthening and Repair of concrete structures using externally bonded FRP sheets and laminates.

   b- Reinforcing flexural concrete elements using FRP rods.

2- Accordingly, the code does not address the other applications listed in section 1-1-2.

1- The provisions of code provide the minimum acceptable requirements for the design, construction, review and quality control for the applications listed in section 1-2-1, a & b.

4- The design of both the strengthening works using FRP composites, and the concrete elements reinforced with FRP rods must satisfy the design principles of the ultimate strength and serviceability limit states of the Egyptian reinforced concrete code, ECP 203.

5- The design of FRP works shall be performed and approved by a licensed consulting engineer. The construction and the quality control of all FRP works shall be carried out in accordance with the design drawings and specifications of the project, under the direct supervision of the licensed consulting engineer. The supervising engineer shall be knowledgeable of design and installation of FRP systems

6- The installation of all FRP works should be carried by a certified contractor specialized in FRP works under the direct supervision of the consulting supervising engineer of the project. The contractor shall demonstrate competency for the installation procedures of the FRP system used in the project.

7- The FRP materials shall be supplied from a known source. The supplied materials shall be certified with clear statements indicating the country of origin and manufacturing along with the properties and the expiry dates of the FRP constituent materials. The constituent materials shall form the ingredients of a well tested comprehensive FRP system registered in the name of the producers. Accordingly, All FRP materials shall be supplied from the same source. Also, prior to the application of any FRP system, the properties of the FRP system and constituent materials shall be verified through quality control testing. FRP systems that have not been fully tested shall not be considered for use.

8- FRP strengthening and repair works shall be continuously monitored for the duration of time specified in the project's specifications in order to guarantee that the quality of such works and their effectiveness has been maintained.

9- Compliance with the requirements of the design and construction provisions of this code does not relieve the engineer of record of a project from any legal responsibilities.

1.3 OBJECTIVES OF THE CODE

The main objectives of this code are to guarantee that structures and parts thereof that are reinforced or strengthened in accordance with the provisions of the FRP code shall satisfy the deflection and crack control requirements of the serviceability limit states of the Egyptian code for concrete structures, ECP203, while guaranteeing that the safety of the structure against distress, collapse, and instability are also satisfied in accordance with the requirements of the Egyptian FRP code and the Egyptian code for concrete structures, ECP203 .

1.4 DESIGN FUNDAMENTALS

1-Long-term exposure of FRP works to various types of environments can reduce the tensile properties, creep-rupture and fatigue endurance of FRP laminates. In addition, exposure of FRP works to elevated temperatures and fire can adversely affect the effectiveness of the strengthening works. Accordingly, the material properties used in design equations shall be reduced according to the environmental exposure condition, as given in Chapter 3 of this code.

2-Strengthening and Repair of structures:

a. The strengthening and Repair applications considered in the code is limited to the use of externally bonded FRP sheets and laminates. Such works can be classified as follows :

- **Bond-Critical Applications:** This type of application depends on the existence of complete bond between the concrete substrate and FRP composites. Therefore, the existing concrete substrate strength is an important parameter for bond-critical applications, including flexure, tension, shear and torsion strengthening.
- **Contact-Critical Applications:** This type of applications relies only on the intimate contact between the FRP system and the concrete Substrate. Such applications include but are not limited to the confinement of columns for the increase of their ultimate strength and ductility by wrapping the columns using FRP sheets.

The design and installation of FRP composites for each of the preceding two applications are different and each requires special considerations.

b- The use of FRP laminates for flexural strengthening of reinforced concrete members will always reduce the ductility of the original member. In some cases, the loss of ductility is significant and can result in a brittle failure mode. As a result, and unlike the requirements of the Egyptian concrete code, ECP203 the Egyptian FRP code addresses the cases of both ductile and brittle failure modes of FRP strengthening and repairing of flexural concrete members. Accordingly, the material resistance factors for both concrete and steel for the cases of brittle failure mode should be raised above the usual level of the ductile failure mode specified in the Egyptian concrete code, ECP203, as given in Chapters 3 and 4 of this code. Also, values of material resistance factor for FRP composites are assigned related to the degree of ductility of the resulting failure mode of the strengthened element, in addition to all durability-related criteria, as given in Chapters 3 & 4 of this code. While FRP systems are effective in strengthening concrete members for flexure and shear and providing additional confinement for columns, other modes of failure may be unaffected by FRP systems. It is, therefore, important to ensure that all members of a structure are capable of withstanding the anticipated increase in loads associated with the strengthened members and their strength shall be in full compliance with the requirements of the Egyptian Code for Concrete Structures, ECP 203.

3-Concrete Flexural Members Reinforced With FRP Bars

The applications involving concrete members reinforced with FRP bars are limited only to the use of FRP as tension reinforcements for flexural members such as beams and slabs, as well as shear reinforcement for beams. FRP bars shall not be used as compression reinforcements for concrete elements including columns and compression reinforcements in flexural members. The design philosophy of concrete members reinforced with FRP bars is based on the limit states design philosophy of the Egyptian concrete code, ECP203. However, due to the brittle failure mode of both FRP bars and concrete, the failure mode of such flexural elements will always be brittle. Accordingly, the material resistance reduction factors for concrete shall be raised above the usual level of the ductile failure mode specified in the Egyptian concrete code, ECP203. Also, values of material resistance reduction factor for FRP composites shall reflect the brittle mode of the failure of such elements, as given in Chapter 5 of this code.

Unlike the recommended tension failure mode of flexural concrete members reinforced with steel bars in accordance with the Egyptian concrete code, ECP203, concrete crushing failure mode is marginally more desirable for flexure members reinforced with FRP bars than tension failure of FRP bars since compression failure mode exhibits some plastic behavior before failure, while failure of FRP bars is sudden and catastrophic. This requirement can be fulfilled in the cases of rectangular section. However, for flanged sections, both tension and compression failure modes are acceptable in governing the design of sections reinforced with FRP bars. Accordingly, the material resistance factors for concrete and FRP shall be raised to the level that will reflect the degree of brittleness of the mode of failure, as given in Chapter 5 of the code

CHAPTER TWO

PROPERTIES OF FIBER REINFORCED POLYMER COMPOSITE MATERIALS

2.1. General

This chapter gives an introduction to the constituent materials of fiber reinforced polymers including all resins and fibers through emphasizing the behavior and the use of the primers, putties, saturates adhesives, protective coating, the commercially available fibers, and the physical and mechanical properties of polymers and fibers. Moreover, this chapter presents the products of fiber reinforced polymers by its variant types and properties either in the form of fiber sheets or fabrics impregnated with a saturating resin on-site, or in the form of fiber sheets or fabrics that are pre-impregnated with a saturating resin in the manufacturer's facility, or in the form of rods, or in the form of pre-fabricated structural shapes. The physical and mechanical properties of fiber reinforced polymer sheets and fiber reinforced polymer bars are discussed in this chapter.

Furthermore, this chapter presents the basics for shipping; storing and handling of fiber reinforced polymeric materials, and specifies the quality control and quality assurance indices for fiber reinforced polymer products through the inspection, evaluation and acceptance procedures.

The properties of fiber reinforced polymers and its constituent materials vary according to the manufacturer, and the manufacturing process, therefore, the material properties described in this chapter are generic and do not apply to all commercially available products, and it is obligatory to consult the manufacturer to obtain the relevant characteristics for a specific product and the applicability of those characteristics.

Fiber reinforced polymers and its constituent material such as fibers, resins, primers, putties, saturates, and adhesives are subjected to continuous development in its types, physical and mechanical properties, and methods and techniques of manufacturing and applications. Therefore, it is recommended that the design engineer should have to enrich and update his background and data base about these materials periodically.

Due to the variation in the material properties of fiber reinforced polymers and its constituent materials from one manufacturer to another, it is recommended to use the components of the entire system from the same manufacturer for the same application, and do not mix fibers, polymers, or adhesives from different sources to ensure the chemical and mechanical consistency of the system components.

2.2. Constituent Materials of Fiber Reinforced Polymer Systems

The constituent materials of the fiber reinforced polymers systems, that is used to strengthen and retrofit existing concrete structures, include all resins, putties, saturates, adhesives, protective coating, common available fibers, and temporary protective materials.

2.2.1Resins

2.2.1.1 Introduction

Resins are materials with a high molecular weight that reach about hundred thousands of repetitive units named monomers. Resins are considered polymers in a viscous state that is close to Gum like materials. Resins are either composed of carbon and hydrogen atom basis, so they are named organic polymers, or they are composed of Silicon, or Phosphor, or Sulfur atom basis, so they are named inorganic polymers.

The word polymer is a general word, therefore, the modulus of elasticity is used to specify and differentiate between the different types of polymers as follows:

a. Polymers are considered Elastomers when they have a modulus of elasticity (E) less than 100 N/mm^2.
b. Polymers are considered Fibers when they have a modulus of elasticity (E) greater than 3500 N/mm^2.
c. Polymers are considered Plastics when they have a modulus of elasticity (E) in between the above mentioned values, i.e. when E is greater than 100 N/mm^2 and less than 3500 N/mm^2.

Polymers could be generally classified to two main parts based on their thermal behavior as follows:

a-**Thermoplastic**; this type melts by heating and hardened by cooling, and it could be reshaped several times by subjecting it to heating and cooling cycles. The types of this class differ either because of its self components or because of adding a specific material to it.

b-**Thermosets;** this type do not melt by heating, however, it completely hardened by cooling. This type is classified by its good electrical properties. Thermosets polymers that do not melt when subjected to elevated temperatures after being hardened and strengthened with fibers are characterized by its high strength to tension, compression, impact, creep, temperature, water and chemical effects. Examples of this type are; Glass fiber reinforced polyester, Carbon, Glass, or Aramid fiber reinforced epoxies.

In some cases, putty fillers are added to the polymers. Putty fillers are fine solid substances such as fine sand, cement, calcium carbonate, silica, mica, and others, and they are added to decrease the cost of the product, improve its properties, and increase its strength specially when used for structural works.

Additives such as plasticizers may be also added to help in simplifying the formation of the product or any other additives that works on improving the properties such as elasticity, and rigidity, or humidity, and fungi resistance, or improve the electrical properties and fire resistance of the product. Also, mineral oxides may be added to color the final product.

2.2.1.2 Resin Types

a. Polyester Resins

Non-saturated polyesters are resin polymers that are usually used in the production of structural component parts. These resins are in the form of low viscous liquids during the operation process and up to curing. However, materials that are partially produced and contain fibers can be used under certain temperatures and atmospheric pressure. A variety of the commercially non-saturated polyester resins are available in the market.

b-Epoxy Resins

Epoxy resins are available in different degrees of viscosity and they are mixed with other hardeners or curing material. The characteristics of the epoxy resin allow for circulating it in a partial curing state or in an advanced curing state, and it is generally known that it is a pre-pregnated product (Prepreg). In case of having fibers in the constituent materials, the product can be formed in mould form or rolled in the form of tapes in the room temperature.

Although some of the epoxies get hardened at a temperature of about 30ºC, however all epoxies may need to be subjected to few degrees of temperature before curing to reach the required performance.

The cross linking process for epoxies starts by using hardeners, and there are several methods for curing which are available in the market and could be used. The Curing time and increase in temperature required for the polymerization process depends on the type and amount of the hardening material used. Some of these hardeners work at room temperature, however most of the hardeners require increasing the temperatures and in some cases some additives named accelerators are added to the liquefied epoxy resins to accelerate the reaction and decrease curing time. Epoxy resins can be cured at temperatures ranging from room temperature and up to an elevated temperature of 175 ºC, at which the final curing is done.

Some hardeners require special consideration during handling, besides, the resins and the hardeners may cause skin allergy.

In comparison to the polyester resin, epoxy resins could provide the following general performance characteristics:

- The possibility of having a wide range of physical and mechanical properties due to the variance in the additive materials.
- There is no volatile material developed during curing and workability process.
- The shrinkage rate is decreased during curing process.
- Excellent resistance to chemicals compounds and solvents.
- Good adhesion with fillers, fibers, and substrates.
- The cost of the adhesive matrix is generally less than that of the Isopolyester or Vinylester.
- Care should be considered during the workability of epoxies to keep its resistance to humidity.
- The curing time may be long.

2.2.1.3 Mechanical Properties of Resins

- The main role of resins when reinforced with fibers is to fix the fibers in place and in a specified orientation, to develop the bond between the fibers, distribute the load over the fibers, and to protect the fibers from deterioration, abrasion, collision, and any other environmental effects that could have a negative impact on the fibers.
- The physical and mechanical properties of a polymer vary according to its chemical composition and manufacturing process, which affects the properties of the final product, therefore, the manufacturer should be consulted to obtain the relevant characteristics for the product.
- The physical and mechanical properties of polymers are affected by the environmental factors such as atmospheric temperature and humidity which accordingly affect the properties of the final product; therefore, a good choice should be made to select the convenient polymer for the proposed application.

- The physical and mechanical properties of polymers are specified by performing the required standard testing to assure these properties. Moreover, it is mandatory in some application to perform the durability test to determine its behavior and how far it is affected by the environmental factors.
- Table (2-1) shows guideline values of the mechanical properties for some of the polymers used in reinforcing fibers with emphasize on the tensile strength, modulus of elasticity, and maximum strain at failure.

Table 2-1: Guideline Values for the Mechanical Properties of Polymers

Polymer Type	Specific Weight	Tensile Strength N/mm^2	Tensile Modulus of Elasticity kN/mm^2	Maximum strain (%)
Epoxy	1.4 – 1.1	90 - 50	3.0	8.0 – 2.0
Polyester	1.2	65 - 50	3.0	3.0 – 2.0
Vinylester	1.15	80 - 70	3.5	6.0 – 4.0

2.2.1.4 Considerations on the Use of Resins

Resins used as a part of the fiber reinforced polymers that are used in repair and strengthening works should fulfill the following requirements:

- Achieve very high adhesive force with the concrete substrate
- Achieve very high adhesive force with fibers or fiber reinforced polymers.
- Achieve high resistance to the surrounding environmental conditions that the concrete elements might be subjected to such as humidity, minerals, elevated temperatures, and chemicals.
- Convenient viscosity.
- Filling capability.
- Convenient workability time before hardening.
- Consistency with the polymer matrix which is used to fix the fibers in its place, and mainly distribute the stresses between the fibers and the surrounding matrix, also, to protect the fibers from the environmental or mechanical attack, and this is similar to the role of concrete in reinforced concrete.

2.2.1.5 Workability considerations for Resins

Workability and final quality of the composite material system depend to a large extent on the properties of the surrounding polymeric matrices such as the viscosity, and the conditions of the required curing system. Also, the physical properties of the polymeric matrix should be taken into consideration while selecting the manufacturing process to be used for impregnating the matrix with the fibers to produce a 3-dimensional final product.

2.2.1.6 Relationship between Polymeric Matrix and Reinforcing Fibers.

The polymeric matrix provides the protection and the shape of the fibers. The chemical, electrical, and thermal behavior may be affected by the type of polymeric matrix selected, however, the role of this matrix highly exceeds this effect, as it fix the fiber in its place and orientation. Moreover, when loaded, the matrix distributes the stresses on the fibers. The polymeric matrices should have a high elongation values at failure compared to that of the fibers, and it also should not shrink to a large extent or higher rates during the curing process to avoid having internal stresses on the reinforcing fibers.

2.2.2 Fiber Reinforcement for Fiber Reinforced Polymers

2.2.2.1 General

- Fibers are manufactured from different materials with diameter in the range of 5 – 20 micrometers in the form of long threads placed in parallel either unidirectional or bidirectional.
- Fibers are characterized by its high strength and modulus of elasticity when compared to the raw material from which these fibers have been produced.
- Fibers used to reinforce polymers should be characterized by its high strength and modulus of elasticity besides its constant thermal, chemical and other properties. The most common types of fibers used in engineering applications are; Glass, Carbon and Aramid fibers.
- By gathering these fibers into a convenient polymeric matrix a thin layer of fiber reinforced polymer is formed called laminate, several layers of laminates are glued to each other to reach the required thickness of the fiber reinforced laminates. The fibers orientation and direction in each laminate could be controlled during the preparation and production process, also the sequence of adding these laminates to each other could be controlled, so we can finally achieve the required physical and mechanical properties.
- Fibers are considered the main element in resisting the load in the fiber reinforced composites, since the physical and mechanical properties of the composite material depends mainly on the type, length, and properties of the fibers used as well as it depends on the ratio between the volume of fibers used to the total volume of the composite material, and the direction and

orientation of the fibers in the matrix. Also, it depends on the adhesive force or bond between the fibers and the polymeric matrix.

2.2.2.2Fiber Types

a. Glass Fibers

- These fibers are available in variant types, the most important types are:
- E-Glass: This type contains a high percentage of Aluminum and boric acid which results in weakening its resistance to alkalis.
- S-Glass: This type is characterized by high tensile strength and modulus of elasticity higher than E-glass, however, it lakes alkaline resistance.
- AR-Glass: This type is characterized by its high resistance to alkaline solutions because it contains a percentage of zircon elements, and also has a tensile strength and modulus of elasticity close to that of E-glass.

Glass fibers are characterized by its cheap price compared to other types of fibers, however it is defective by their high creep as well as its higher density compared to other types of fibers, though it is less than that of concrete and steel. Glass fibers are also characterized by their resistance to wear and corrosion, and are a good conductor of electricity, however they are affected by alkaline solutions, therefore, glass fibers should be protected by using convenient resins or by protective coating.

Glass fibers have very active surfaces and can easily deteriorate during handling. Therefore, glass fiber surfaces are covered with protective layer as a first step just after the start of fiber manufacturing process. This protective layer contains an adhesive agent with organic effect that works as a reagent for bonding between the fibers and the polymeric matrix. Also, this protective layer provides workability and humidity protection. The type of the protective layer and the adhesive reagents is selected by the manufacturers based on the manufacturing conditions and the workability of the polymeric matrices for the required product.

When applying tensile loads on glass fibers they behave linearly elastic up to failure with a modulus of elasticity ranges between 70 – 90 kN/mm^2, and with an ultimate strain at failure in the range of 3.00% to 5.5%.

b.Carbon Fibers

Carbon fibers are characterized by having the highest tensile strength and modulus of elasticity compared to other types of fibers, as well as its lower densities; however it is defective by its brittle failure since the failure occurs at a relatively small elongation although this corresponds to ultimate stress at much higher values when compared to other types of fibers. Moreover, Carbon fibers are characterized by their resistance to wear and corrosion, as well as by having a negative coefficient of thermal expansion. Furthermore, it is characterized by being good conductor of electricity which makes it unsuitable in some structures or elements that are exposed to electric fields. Carbon fibers resist corrosion, though it might results in the corrosion of other metals when being in contact such as steel and aluminum. Carbon fibers are available in a variety of forms, the most common types are:

- General Purpose Carbon Fibers
- High Strength Carbon Fibers
- Ultra-High Strength Carbon Fibers
- High Modulus Carbon Fibers
- Ultra High Modulus Carbon Fibers

c.Aramid Fibers

Fibers behave linearly elastic in tension and are characterized by their high tensile strength and high strain up to failure. Moreover, they are characterized by their ability to absorb energy, and fatigue resistance, that makes them convenient for use in structural elements that are subjected to impact forces. They are also characterized by their non-linear elastic behavior in compression, as well as their disability to sustain higher values of compression strength. They also have negative coefficient of thermal expansion and they are available in two types; one type has high modulus of elasticity and the second one has ultra-high modulus of elasticity.

2.2.2.3 Mechanical Properties of Fibers

- Fibers are characterized by their high strength and modulus of elasticity when compared to the raw material from which these fibers have been produced. As the aspect ratio increases, the efficiency of distributing the load between the fibers and the polymeric matrix increases. This will result in achieving the ultimate use of the properties of these fibers and makes the fibers convenient materials for reinforcing the polymers.
- The reinforced fibers are characterized by having constant thermal and chemical properties.
- The properties of reinforced fibers depend on the type of fibers, manufactured source, and the processing methods. So, the real properties of the product shall be obtained from the manufacturer itself. Table (2-2) illustrates guideline values of the mechanical properties for the fibers

Table 2-2: Typical Mechanical Properties for Fibers in Tension

Type	Tensile strength N/mm²	Modulus of Elasticity kN/mm²	Ultimate Tensile Elongation %
E- Glass	1900-2700	70	3.0-4.5
S- Glass	3500-4135	85-90	4.5-5.5
General Purpose Carbon	2050-3800	215-235	1.2-1.4
High Strength Carbon	3800-4800	215-235	1.4-2.0
Ultra-High Strength Carbon	4800-6200	215-315	2.3-1.5
High-Modulus Carbon	2500-3100	350-515	0.5-0.9
Ultra High Modulus Carbon	2100-2400	515-700	0.2-0.4
Low-Modulus Aramid	3500-4100	70-80	4.3-5.0
High-Modulus Aramid	3500-4100	115-130	2.5-3.5

2.2.2.4 Forms of Fiber Reinforcement

There are many forms of Fiber Reinforcement. The commonly used forms are:

a.Roving

Roving is the main form for continuous fibers. It is a collection of a group of fibers/straps or being in the case of Direct-Pull in which the roving is formed at once which results in more homogenous product which reduces the bending in the roving groups subjected to unequal tensile loads.

b.Woven Roving

Roving type mentioned before is used for producing Woven Roving. In this type, the fibers are orientated in at least two planner directions such as

($0/90^o$) orientation or ($+45^o/-45^o$) orientation or in other orientations depending on the manufacturing process. These products are sold in weight per square meter base.

a- Mats

They are fibers chopped into flakes or pellets and arranged in a random manner in two dimensional planes. Then, these fibers tows are put on a continuous shipper and pass through a machine in which the resin is spread over them. This resin is hardened by temperature which can bond the mat. Also, this resin (as a bonded material) penetrates the Polyester or Vinylester which allows the mat to be formed to the required shape.

c.Combined Product

It is possible to incorporate the woven roving with fiber mat which can be cut into pellets. There are many techniques to achieve this process. One of these techniques is the bonding of roving with the mat together using a resin similar to that used in the chopped fibers into pellets. Another technique begins with spreading the chopped fibers on the surface of roving woven followed by penetration process to protect these fibers.

2.2.2.5 Temporary Protection

Fiber Reinforced Polymers laminates or roving may be subject to high temperature or direct rains or dust or high sun rays or other parameters during the formation of the composite material which leads to unsuitable curing or hardening for the resins. Temporary Protection by means of tents or plastic sheets may be required during the processing of composites material until the complete curing and hardening of resins. In case of using studs, the fiber reinforced polymers must be cured and hardened completely before releasing these studs and allowing for the structural elements to carry the additional design loads. It shall be referred to the designer engineer and consult the system's manufacturers for giving the recommendation in case of decay in the fiber reinforced polymers during fabrication.

Putty Fillers

The putty is used to fill small surface voids in the substrate, and to provide a smooth surface, as well as to prevent the formations of bubbles during the implementation of the saturated resin when applying the fiber reinforced polymers and this shall be performed according to Section Four of Chapter Four of this code.

Adhesives

Adhesives are used to bond procured fiber reinforced polymers to concrete substrate. They are also used to bond together multiple layers of procured fiber reinforced polymers laminates.

Protective Coatings

The protective coating is used to protect the bonded fiber reinforced polymers from potentially damaging environmental effects.

2.3 Fiber Reinforced Polymers (FRP)

The following sections will introduce the commonly used FRP composites. The most common type is the laminates used in externally bonded for strengthening and rehabilitating deteriorated structural elements. In addition, they are also used to increase its load capacity due to either change of the structure use and to correct design and repair of construction faults. The FRP bars can be used as main reinforcement for concrete sections and strengthening of concrete structures.

2.3.1 Design Considerations for Fiber Reinforced Polymers (FRP)

- The FRP composites performance depends on the formation of its materials properties such as; type and adhesive polymer surrounding area, type, length and properties of the resistant reinforced fibers to main loads, and fibers percentage and direction. Also, the performance depends on the adhesive force or the bond between fibers and the adhesive polymer, surrounding area, the homogeneity between the materials, and the materials compatibility.
- Arranging the fibers through mono direction inside the composite, results in maximum tensile strength and maximum modulus of elasticity in the fibers axis direction. In case of arranging the fibers in bidirectional, it will show different strength in coordination with the different angles. The mechanical properties in any of the directions are proportional to the fiber volume fraction in that direction.
- Many of the FRP composites have high internal damping property. This leads to high absorption for vibrations and fluctuations through the material and reduce the probability of transmitting them to the adjacent structures. This behavior is suitable for structures subjected to vibrations or temporary loads in a short time span.

The design philosophy and criteria are detailed in Sections 4.3.1, 4.3.2 and 4.3.3 in Chapter 4.

2.3.2 Fibers Reinforced Polymers Laminates

2.3.2.1 Introduction

- The laminate is defined as the single layer of fibers, it could be laminate fabricated from long fibers placed parallel in one direction or intersected directions and impregnated with polymer. Where it is considered a ready laminate to be applied to the surface, also fibers can be partially impregnated with resin and delivered in the shape of unidirectional yarn or perpendicular directions and fixed by adhesives on another layer or on the required surface. Also the fibers can be reduced into small lengths and added to the polymer during mixing then poured in a block and cured till hardness forming a layer, and this is not discussed in this code.

- The classifications of different types of fibers reinforced polymers laminates depends on its handling form to the site and application method as follows:.

A .Wet and Dry Lay-ups

The process of wet and dry lay ups is described in details in Section 4.2.4 in Chapter 4.

B . Prepreg Systems

Section 4.2.4 in Chapter 4 includes detailed description of the prepeg systems.

C .Precured Systems

The different precured systems are included in Section 4.2.4 in Chapter 4.

2.3.2.2 Physical Properties of Fiber Reinforced Polymers Laminates

2.3.2.2.1 Density

The density of the FRP laminates with different types of fibers ranges from $(0.2 – 3.38)\times10^{-3}$ g/mm^3 and these values are 4 – 6 times less than the steel reinforcement density used in reinforcing concrete elements, as shown in Table (2 - 3).

2.3.2.2.2 Coefficient of Thermal Expansion

The coefficient of thermal expansion of FRP laminates reinforced with unidirectional fibers in the longitudinal direction differs from that in the transverse direction. The variation depends on the type of fiber used, in addition to the resin type and the fibers volume fraction. Table (2 – 4) shows coefficient of thermal expansion for both the longitudinal and transverse directions for traditional unidirectional fiber reinforced polymers. The negative values for the coefficient of thermal expansion shown in the table indicate that the used material shrinks when temperature increases and expands when temperature decreases. It is known that the concrete coefficient of thermal expansion is (7×10^{-6} - 11×10^{-6}/m/°C) although reinforcement steel coefficient of thermal expansion equals (11.7×10^{-6}/ m/°C).

Table (2 – 3) Guide for Fiber Reinforced Polymers Laminates Density (g/mm³)

Steel Reinforcement	Carbon Fiber Reinforced Polymers	Glass Fiber Reinforced Polymers	Aramid Fiber Reinforced Polymers
7.9×10^{-3}	$(1.2 – 2.1) \times10^{-3}$	$(1.5 – 1.6) \times10^{-3}$	$(1.2 – 1.5) \times10^{-3}$

Table (2 – 4) Guide for Coefficient of Thermal Expansion of FRP Laminates*, Concrete and Reinforcing Steel

<table>
<tr><th rowspan="2">Fibers Direction</th><th colspan="5">Coefficient of Thermal Expansion $\times10^{-6}$ / °C</th></tr>
<tr><th>Glass Fiber Reinforced Polymers</th><th>Carbon Fiber Reinforced Polymers</th><th>Aramid Fiber Reinforced Polymers</th><th>Concrete</th><th>Reinforcing Steel</th></tr>
<tr><td>Longitudinal fibers Direction α_L</td><td>6 to 10</td><td>-9 to 0</td><td>-6 to -2</td><td rowspan="2">7 to 11</td><td rowspan="2">11.7</td></tr>
<tr><td>Transverse fibers Direction α_T</td><td>19 to 23</td><td>22 to 50</td><td>60 to 80</td></tr>
</table>

*These values for fibers content percentage 50 to 70 % of volume

2.3.2.2.3 Effect of High Temperature

Polymers modulus of elasticity obviously decreases due to the alteration of its particles formation when the temperature reaches the degree where the material physical formation changes (T_g) (glass transition degree), where (T_g) depends on resin type. In most cases, the temperature varies from (60 to 120° C). The FRP reacts thermally better than polymers alone due to the presence of fibers. In case of increasing temperature, it continues to sustain some load in the longitudinal direction up to (T_g). Where, the values of T_g are (1000° C) for glass fibers and (175° C) for aramid fibers and carbon fibers bare temperature degree more than (275° C).

The bond between fibers and concrete surface is one of the main concerns that must be taken into consideration especially in cases that depend on the bond between concrete and FRP laminates. At high temperature when it reaches the degree where the material formation changes (T_g), the mechanical properties decrease significantly and the polymers losses its capability in transferring the effective strain from concrete to the used fibers.

2.3.2.3 Mechanical Properties of FRP laminates

2.3.2.3.1 General

- In this part the mechanical properties of FRP laminates under short period of loading are presented. Other types of time dependent effect such as creep, fatigue, and durability will be discussed in chapter (3).
- The properties of prefabricated FRP system depend mainly on the source of FRP system such properties must be tested for acceptance before application.
- Appendix 2 presents typical mechanical properties of FRP laminates and its component.
- Physical and mechanical properties are determined experimentally as outlined in appendix 2 (FRP tests).
- Mechanical properties of in-place FRP system are calculated considering the net area of fiber. In case of prefabricated FRP systems the gross area including fiber and polymer should be considered.

Table (2-5) is considered a guide of some mechanical properties of some commercial GFRP, CFRP and AFRP with fiber volume fraction of 50%. These properties are tensile strength; shear strength; modulus of elasticity and Poisson's ratio. Typical ultimate tensile strength of some FRP systems per unit width of laminates is shown in table (2-6).

Table (2-5): Mechanical Properties of Some Available Commercial FRP Laminates

Type of Fibers/polymer	Glass – E / Ester Vinile	Carbon / Epoxy	Aramid / Epoxy
Longitudinal Tensile Strength (N/mm^2)	610	1448	1400
Transverse Tensile Strength (N/mm^2)	49	52	12
Shear Strength (N/mm^2)	16	93	34
Longitudinal Modulus of Elasticity (KN/mm^2)	54	181	76
Transversal Modulus of Elasticity (KN/mm^2)	14	10	6
Shear Modulus of Elasticity (KN/mm^2)	5	7	2
Poisson's Ratio	0.25	0.30	0.34

- Mechanical properties of FRP laminates may be calculated by equations considering their dimensions and fiber volume fraction. The results of these equations are approximate due to ideal approximations and assumptions such as materials properties and full contact between FRP systems, but experimental results should only be considered. The following equations used for estimating some mechanical properties of FRP considering ultimate strength of fibers and polymer.

$$E = E_f V_f + E_m V_m \qquad (2\text{-}1)$$

$$f = f_f V_f + f_m V_m \qquad (2\text{-}2)$$

Where:

E = Modulus of Elasticity of Composite Material
f_f = Fiber Strength
f_m = Resin Strength
E_f = Modulus of Elasticity of Fiber
E_m = Modulus of Elasticity of Resin
V^f = Fiber Volume Fraction
V_m = Resin Volume Fraction

2.3.2.3.2 Tensile Behavior

- The FRP materials when loaded in direct tension, load-elongation relationship will be linear and brittle failure occurs without yielding.

- To determine the tensile strength of FRP laminates, standard tension test must be applied according to test in procedure of this code using special test grips.

- The tensile strength of FRP laminates is defined as the ultimate stress on the net area of fiber or on gross area of FRP laminates considering the fiber volume fraction. The tensile strength is calculated as the average of the ultimate tensile strength minus three times the standard deviation. The ultimate strain is calculated similar to calculating the tensile strength.

- The tensile strength of a prefabricated FRP laminates is determined from factory report from lab test results which describes the procedure, test setup, number of samples and standard deviation.

- The tensile strength of FRP laminates depends on the properties of fibers such as fibers shape, dimensions, orientation and fiber volume fraction and also method of fabrication, curing and fabrication quality control.

Table (2-7) gives typical values of FRP laminate (2.5mm thickness) for tensile strength, modulus of elasticity and Poisson's ratio for fiber volume fraction 40-60%, and also shows the effect of fiber orientation relative to loading direction. The zero angle indicates that the fiber and loading are in the same directions. In case of (0^o /90^o) indicates that the fiber are equally distributed in longitudinal and transverse direction with respect to loading direction. In case of (-45^o /+45^o) indicates that the fiber are equally distributed in longitudinal and transverse direction and inclined with 45^o to loading direction.

Table (2-6) Typical Ultimate Tensile Strength for Commercially Available FRP Laminates.

System Description Fiber / Saturated Polymer	Product Orientation	Density x10^{-3} (gm/m^3)	Ultimate Strength (kN/m width)
Ordinary Carbon / Epoxy	Uni-direction laminate	0.2 0.4	500 315
High Strength Carbon / Epoxy	Uni-direction laminate	0.23 0.3 0.62	620 700 960
High Modulus of Elasticity Carbon / Epoxy	Uni-direction laminate	0.30	600
Ordinary Carbon / Epoxy	Two direction laminate	0.30	180
Glass-E / Epoxy	Uni-direction laminate	0.9 0.35	720 230
Glass-E / Epoxy	Two direction laminate	0.3	120
Aramid / Epoxy	Uni-direction laminate	0.42	700
High Strength Carbon / Epoxy	Prefabricated Uni-direction laminate	2.38	3300

Table (2-7) Typical Properties of FRP Laminates with Fiber Volume Fraction 40-60%.

Type of Fiber / Polymer	Angle	Ultimate tensile strength (N/mm^2)		Modulus of Elasticity (kN/mm^2)		Elongation %
		Longitudinal Direction	**Transverse Direction**	**Longitudinal Direction**	**Transversal Direction**	
Glass / Epoxy	0^o	520-1400	35-70	20-40	20-34	1.5 - 3.0
	0^o / 90^o	520-1020	520-1020	15-35	14-35	2.0 - 3.0
	-45^o / $+45^o$	180-280	180-280	15-20	14-20	2.5 - 3.5
High Strength Carbon / Epoxy	0^o	1020-2080	35-70	100-140	100-145	1.0 - 1.5
	0^o / 90^o	700-1020	700-1020	55-75	55-75	1.0 - 1.5
	-45^o / $+45^o$	180-280	180-280	15-30	14-28	1.5 - 2.5
High Properties Aramid / Epoxy	0^o	700-1720	35-70	48-68	48-68	2.0 - 3.0
	0^o / 90^o	280-550	280-550	28-34	28-35	2.0 - 3.0
	-45^o / $+45^o$	140-210	140-210	7-14	7-14	2.0 - 3.0

2.3.2.3.3 Compression Behavior

- The FRP systems are mainly used to carry tensile forces and should not be used as compression reinforcement.
- The compressive strength of FRP laminates depends on the type of fibers, polymer and fiber volume fraction. Failure occurs due to fiber-micro-buckling, shear failure or transverse tensile stresses.
- The compression tests of FRP laminates indicate that the compressive strength is lower than tensile strength. The compressive strength of GFRP, CFRP and AFRP is about 55%, 78% and 20% of their tensile strength respectively.
- Test results on uni-directional FRP laminates indicate that the compressive strength is higher when loaded in direction perpendicular to fiber direction than when loaded in the same direction of fiber. This is due to that polymer compressive strength is higher than its tensile strength, also the fibers with

stand some stresses. In case of AFRP buckling occur under small compression load.

- Test results indicate that modulus of elasticity in compression is higher than in tension.
- The compressive strength of a prefabricated FRP laminates could be obtained from either factory report that should include test procedure, test setup, number of samples and standard deviation, or by conducting tests according to testing procedures explained in appendix 2
- Table (2-7) gives typical properties of GFRP, CFRP and AFRP laminates with fiber volume fraction 40-60% and also show the effect of fiber orientation relative to loading direction.

2.3.2.3.4 Flexural Strength

Detailed information on tensile strength of FRP laminates is given in Chapter Four.

2.3.2.3.5 Shear Strength

Chapter Four includes the information on shear strength of FRP laminates.

2.3.2.3.6 Bond Strength

The bond strength of FRP laminates is discussed in Chapter Four.

2.3.3 Fiber Reinforced Polymer Bars

2.3.3.1 Fields of Applications

Various fields of application of FRP laminates are outlined in Chapter Five.

2.3.3.2 Commercially Available FRP Bars

The commercially available FRP bars for use as reinforcement in concrete structures are either made from Aramid fibers, Carbon fibers or Glass fibers together with the resin. The FRP are manufactured in the form of bar mesh, individual bars, or woven strands. The individual bars have different cross sectional shapes and surface textures; the cross sectional shapes could be square, or circular, solid or hollow, while the surface textures could vary from externally wrapped fibers, or sand coating, or separate ribs. Figure (2-1) shows the most common glass FRP bars.

2.3.3.2.1 Tensile Strength and Modulus of Elasticity of FRP Bars

FRP bars are manufactured with different diameters. The tensile strength is based on the minimum strength available (400 N/mm^2). The bars could be manufactured with higher tensile strength as shown in Table (2-9).For design purposes the tensile strength for the FRP bars could be chosen between F60 and F300 without the need of choosing a specific commercial FRP bars.

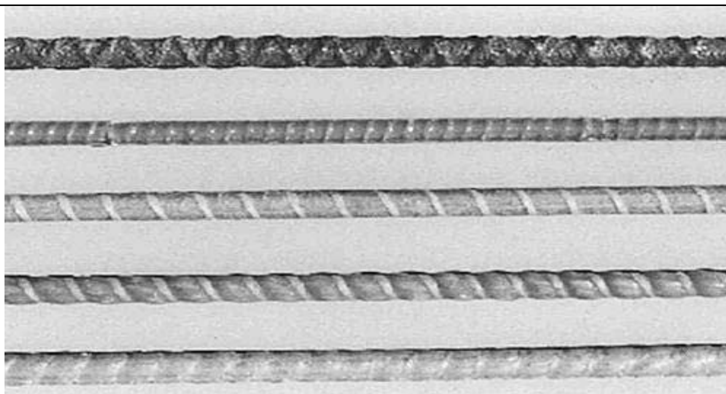


Figure 2-1: Typical shapes of FRP Bars

Table 2-8: Advantages and disadvantages of FRP bars

Advantages of FRP Bars	Disadvantages of FRP Bars
- High longitudinal strength (varies according to the direction and type of loading with respect to the fibers' orientation) - High corrosion resistance (independent on the cover thickness) - Nonmagnetic (does not accept magnetization) - High fatigue strength (according to the type of fibers) - Lightweight (about 1/4 to 1/5 that of steel bars) - Lower thermal and electrical conductivity (Glass and Aramid fibers)	- Lower strength in the transverse direction (varies according to the direction and type of loading with respect to the fibers' orientation) - No yield before the brittle failure - Lower modulus of elasticity (varies according to the type of fibers) - The damage of fibers and resin on exposure to ultra-violet radiation - Decrease of Glass fiber durability with time - Decrease of some Glass and Aramid fibers durability on exposure to alkaline environment - High coefficient of thermal expansion in the transverse direction with respect to concrete - Fire endurance depends on polymer type and the quality and thickness of concrete cover

Table 2-9: Tensile Strength for FRP Bars

Bar Grade	Tensile Strength (N/mm^2)
F60	$f_{fu} \geq 400$
F70	$f_{fu} \geq 500$
F300	$f_{fu} \geq 2000$

The modulus of elasticity is determined during the measurement of the tensile properties of the bars, the lowest value modulus value for each type of fibers should be determined. Designers should choose the lowest modulus of elasticity value for the corresponding fiber type used. If the manufacturer produced FRP bars with higher modulus value than those given in Table (2-10), this will result in FRP bars of higher tensile strength which in turn will result in reduction in the used FRP reinforcement in some applications.

Table (2-10) gives the minimum modulus of elasticity values for FRP bars with different fiber types. The maximum tensile strain for FRP bars should be measured during tensile strength test.

Table 2-10: Minimum Modulus of Elasticity for FRP Bars with \ Different Fiber Types

Bar Type	Modulus of Elasticity x 10^3 (kN/mm^2)
FRP Bars with Glass Fibers (GFRP)	40
FRP Bars with Aramid Fibers (AFRP)	70
FRP Bars with Carbon Fibers (CFRP)	110

2.3.3.2.2 Surface Texture

FRP bars are manufactured with different manufacturing processes which produces various surface textures. The surface texture of the bars is important for its role in developing the bond strength between the bars and the concrete. Figure (2-2) shows three types of FRP bars' surface texture.

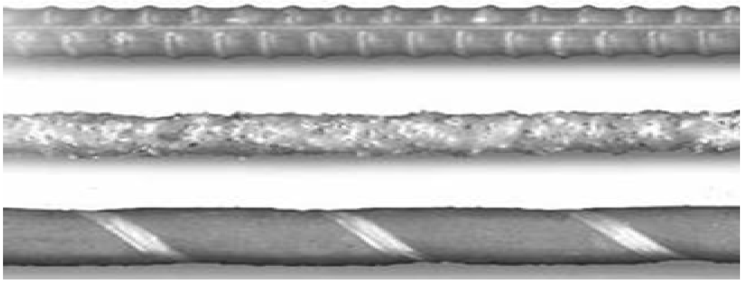


Figure 2-2: Typical Surface Texture for FRP Bars

a) ribbed, b) sand coated, c) wrapped and sand coated

2.3.3.2.3 Bars Sizes

Nominal diameter for FRP bars with ribs is equivalent to the same plane bar with the same cross sectional area, for non-traditional bars such as non-circular (rectangular cross section) or hollow bars, the nominal diameter is equivalent to the circular solid cross sectional bar with the same cross sectional area. The maximum bar cross sectional dimension should be stated besides its nominal diameter.

2.3.3.3.4 Bar Identification

With the variation in grades, sixes, and fiber type of FRP bars, it is essential to provide the bars with identification. A label ticket for each shipment or consignment of the FRP bars shall be provided by the manufacturer. The following information shall be included in the label ticket:

a- Manufacturer identification symbol.
b- A letter to identify the fibers type (G for Glass fibers, C for Carbon Fibers, A for Aramid Fibers, and H for hybrid fibers), this should be followed by the bar nominal bar size according to the standards.
c- Identification for the tensile strength grade.
d- Identification for the modulus of elasticity grade.
e- For non-traditional bars (non circular cross section or hollow) identification for the external diameter or maximum bar cross sectional dimension shall be included.

Example for bar identification:

XXX G # 4-F60 E 6.0

XXX = Manufacturer identification symbols
G # 4 = FRP bar made of Glass fibers number 13 (nominal diameter 12.7 mm)
F60 = Tensile strength grade ≥ 400 N/mm^2

E6.0 = Modulus of Elasticity grade ≥ 40 kN/mm^2

For non-traditional cross sectional bars, extra identification symbols should be added, for example:

XXX G # 4 F100 E40 0.16

Where;
0.16 = Maximum bar cross sectional dimension (mm)

Bar identification should be used in site to check that the required grade and size are used.

2.3.3.2.5 Straight FRP Bars

FRP bars are cut in the machine shop or the manufacturing plant to the specified length.

2.3.3.2.6 Bent FRP Bars

Bending of FRP bars made from thermoset resin should be done before the hardening of the resin, as bending or shaping the FRP bars after hardening is impossible due to its high rigidity after hardening. Heating the bars after hardening is not allowed as it will result in decomposition of the resin, leading to the loss of the FRP strength.

The strength of bent FRP bars is significantly different than those of straight FRP bars. The difference depends mainly on the technique used in bending and the type of the resin. Therefore, the strength of the bent FRP bars should be reduced depending on the test results performed according to test methods described in the testing procedures (Appendix…). Bending could be carried out for FRP bars in which the resin has not been fully cured; bending shall be carried out according to the manufacturer specifications, bending shall be carried gradually and avoiding sharp bending angels which could damage the fibers.

2.3.3.3 Physical Properties of FRP Bars

2.3.3.3.1 Density

The density of FRP bars ranges from 1.20 to 2.1 x10^{-3} gm/mm^3, which is equivalent to 1/6 to 1/4 the density of steel bars, shown in Table (2-11). The lower density reduces the cost of transportation and the ease of handling the bars in site.

Table 2-11: Density of Different Bars x10^{-3} gm/mm^3

Steel	GFRP	CFRP	ARFP
7.90	1.25-2.10	1.50-1.60	1.20-1.40

2.3.3.3.2 Coefficient of Thermal Expansion

The coefficient of thermal expansion of FRP bars differs in the longitudinal direction from that in the transverse direction depending on the type of fibers, resin and the volume fraction of fibers. The coefficient of thermal expansion in the longitudinal direction is mainly affected by the fibers' properties, while the transverse coefficient is affected by the resin properties.

Table (2-12) gives the coefficient of thermal expansion in the longitudinal and transverse directions for FRP and steel bars. The negative sign indicates that the material shrinks on the exposure to high temperature and expands on decreasing the temperature. For reference, the coefficient of thermal expansion of concrete is (7-11x $10^{-6}/^{o}C$) and is assumed to be anisotropic material.

Table 2-12: Coefficient of Thermal Expansion for Different Bars*

Direction	Coefficient of Thermal Expansion x $10^{-6}/^{o}C$			
	Steel	GFRP	CFRP	AFRP
Longitudinal	11.7	6 – 10	(-9) – 0	(-6) – (-2)
Transverse	11.7	21 – 23	74 – 104.0	60 – 80

* Fiber volume fraction ranges from 50% to 70%

2.3.3.3.3 Effect of High Temperature

FRP bars are not recommended to be used in structures in which its integrity depends on fire resistance. FRP reinforcing bars inside concrete will not burn due to the lack of oxygen, but the polymers will be affected by high temperatures and will start to soften. The temperature at which the polymer will start to soften is known as the "Glass-Transition Temperature" (Tg). At temperatures higher than Tg the modulus of elasticity of the polymer will significantly decrease due to the changes in the molecular structure. Tg mainly depends on the resin type and usually ranges between 60 – 82 ^{o}C. In composite materials fibers have thermal properties higher than the resin, so it could withstand loads in the longitudinal direction, while the tensile properties of the composite as a whole decreases due to the decrease in the bond and the load transfer between fibers and resin.

In concrete structures reinforced with FRP bars, the properties of the resin at the surface of the bars are essential for maintaining bond between concrete and the FRP bars. The mechanical properties of the polymer significantly decrease as the temperature approaches its Tg, at which the polymer is unable to transfer stresses between concrete and the fibers. For FRP bars with a Tg ranging between 60-124°C, the bond strength measured by pull-out test was found to decrease by 20-40% at 100°C, and the reduction was 80-90% at 200°C. For FRP bars, the bars failed in tension when the temperature of the bar ranged between 250 – 350°C. Such behavior will result in increasing local crack width and flexural deflections. High temperature should not reach the end regions of the FRP bar in order to maintain the bond strength with concrete.

Structures will collapse when bond strength between FRP bars and concrete is lost due to the softening of the polymer or when temperature exceeds the fibers threshold temperature. For Glass fibers structure collapse will occur at 980°C, and at 175°C for Aramid fibers, while Carbon fibers can sustain temperature up to 1600°C.

The performance and endurance of structures reinforced with FRP bars exposed to fire and elevated temperatures is still under investigation.

2.3.3.4 Mechanical Properties of FRP Bars

The mechanical properties of FRP bars differ greatly from one product to the other. Several factors influence the physical and mechanical properties of FRP bars such as; fiber volume fraction, fiber type, resin type, fiber orientation, dimensions, quality control, and manufacture process. The properties should comply with the standards of the country of origin. FRP bars are identified with different identifications according to tensile strength and modulus of elasticity grades.

2.3.3.4.1 Tensile Behavior

- FRP bars are characterized with linear relationship between elongation and tensile load up to failure. Failure is not preceded with yielding or plastic elongation similar to steel bars.
- Tensile strength depends on fibers' properties which represent the main carrying component, also the shape and dimensions of the fibers, its orientation, its volume fraction with respect to the resin, and its bond with the resin. Manufacturing process, curing and quality control also affect the tensile strength.

- Diameter of FRP bars has an effect on its tensile strength, due to the non-uniform stress distribution on the bar cross section (Shear Lag Effect). The stresses are higher on the perimeter than on the center of the bar. This effect increases by increasing bar diameter, which lowers the efficiency and strength of large diameter bars.
- Tensile strength of FRP bars shall be recorded from the manufacturer and/or supplier report. Tensile strength is the average of the tested specimens minus three times the standard deviation is recorded as the tensile strength. Also the maximum strain is determined similarly.
- Tensile strength of FRP bars shall be carried out in accordance with the standard test method described in the testing procedure. Special testing grips shall be used to avoid stress concentration at gripping ends leading to pre-mature failure of the specimen.
- Table (2-13) gives typical tensile properties of different FRP bars (Glass, Aramid and Carbon fibers) with fiber volume fraction of 50-70% with respect to steel reinforcement.

Table 2-13: Typical Tensile Properties of FRP Bars

Bar Type	Yield Stress N/mm^2	Tensile Strength N/mm^2	Modulus of Elasticity kN/mm^2	Strain Factor %	Maximum Elongation %
Steel	276-517	483-690	200	1.4-2.5	6-12
GFRP	---	483-1600	35-50	---	1.2-3.1
CFRP	---	600-3690	120-580	---	0.5-1.7
AFRP	---	1720-2540	41-125	---	1.9-4.4

2.3.3.4.2 Strength of Bent Bars

- FRP bars could not be bent after resin hardening as they are manufactured from thermoset type resin. FRP bars made from thermoplastic resin type are an exception as they can be reshaped and bent by temperature and/or pressure. Therefore, FRP bars shall be bent during manufacturing process and before hardening of the resin to be able to shape it with the desired rotations and angels.
- Tensile strength at corners and bent sections is reduced by 40-50% compared to straight bar.
- Tensile strength for bent bars shall be determined according to test method described in the standard testing procedure .

2.3.3.4.3 Compression Behavior

- FRP bars are primarily used to resist tensile stresses and it shall not be used to resist axial compression. The FRP bars could be extended in the compression zone to develop the bond length of the bar.
- Compression strength of FRP bars depends mainly on fiber type, its volume fraction and resin type. Failure is expected to occur due to fiber micro buckling or shear stresses or transverse tensile stresses.
- Since there is no standard test to determine compressive strength of FRP bars, it shall be obtained from the manufacturer data sheet. It shall also include the procedure followed.
- Compressive strength values, determined in a separate study on short FRP bars (l/d ranges from 1:1 to 2:1), was found to be lower than tensile strength values. Compressive strength is 55%, 78% and 20% of the tensile strength for GFRP, CFRP and AFRP bars respectively. Also, tests showed that modulus of elasticity in compression is lower than that determine in tension, its value is 80%, 85% and 100% 0f that in tension for GFRP, CFRP and ARFP bars respectively.

2.3.3.4.4 Shear Behavior

- FRP bars have low longitudinal shear strength, this is because shear stresses are carried alone by the resin and the fibers have no resistance to transverse stresses.
- FRP bars are not subjected to shear stresses even when used to resist shear forces in reinforced concrete sections, because the developed stresses are tensile stresses in the bars at the locations of cracks formation.
- Shear strength could be enhanced by including inclined or transverse fibers to the longitudinal fiber direction during the manufacturing processes. This could be done by wrapping extra fibers with the longitudinal fibers.
- Shear strength of FRP bars could be obtained from the manufacturer, who shall state the testing method and procedure used and number of specimens tested and its results.

2.3.3.4.5 Bond

- Bond strength between concrete and FRP bars depends on the mechanical properties of the bars, and surface texture. The bond between FRP bars and concrete is developed by:
  - Adhesion between FRP surface and concrete by chemical bonds
  - Friction against slip
  - Mechanical interlock due to the surface roughness of the bar and ribs

- Bond strength shall be measured using pull-out test explained in the testing procedure appendix. In the manufacturer report, the type of test, number of specimens and its results shall be included.
- The inclusion of ribs, longitudinal or helical, or using sand coating shall be considered in manufacturing the FRP bars to increase the bond strength with concrete. The quality control is essential in all production processes.

2.3.4 FRP Sections

- FRP sections are manufactured by different production processes such as; fiber pultrusion, filament winding and mold casting. FRP sections are delivered in the required length to be assembled by bonding to produce the desired cross section. FRP sections could be used separately or to strengthen concrete elements.
- FRP sections are available in different forms and shapes such as; plates, grids, pipes, angles, and shells, with different thickness and dimensions. Any desired shape and dimension of the FRP sections could be manufactured.
- The physical and mechanical properties of FRP sections varies significantly depending on the type of fibers, resin, fiber volume fraction, fiber orientation in each layer. The properties of FRP sections also depend on its shape, dimension, number of layers and its sequence. This gives flexibility to designers to choose the required section, materials, fiber orientation to achieve desired properties and behavior of the section.
- Properties of FRP sections depend on manufacturing processes, and quality control. To ensure the quality of the produced sections, quality control tests on used materials shall be followed.
- The behavior and performance of structures strengthened by FRP sections depends on the properties of the sections used, and the composite behavior of the FRP section and the concrete element. The bond between FRP sections and concrete shall be ensured and tested.

2.3.5 FRP Hybrid Systems

- FRP Hybrid systems means the use of more than one type of fiber in the production of FRP products, or the use of different FRP products (plates, laminates, bars, sections) together or with another materials.
- Designers sometimes use hybrid systems to utilize the physical and mechanical properties of each of the used materials and to offset the disadvantages and deficiency of the others, in order achieve design requirements and economics.
- Design of hybrid systems requires extensive familiarity with the physical and mechanical properties of the used materials besides its chemical

composition in order to avoid any incompatibility and chemical reactions that could affect the long term durability.

- Design using hybrid systems requires full knowledge and experience with the different materials used and systems to achieve the structural performance required.
- The use of hybrid systems in structures is still new; therefore structural models should be tested and investigated prior to application in order to get full knowledge pertaining to its behavior and performance.

2.4 Shipment, Storage and Handling

2.4.1 Shipment, Storage and Handling of FRP Laminates

2.4.1.1 Shipment

Components and constituents of FRP laminates shall be packed and shipped according to national or international packing and shipping rules, codes and regulations. The materials shall be classified according to its type in order to be safely handled especially if it is corrosive or toxic material, for example packaging and shipping of thermoset resin.

2.4.1.2 Storage

a) Storage Conditions

Materials shall be stored in accordance with the manufacturer guides in order to maintain the properties of the constituents of FRP laminates. Safety regulations according to national or international standards or according to manufacturer recommendations shall be followed during the storage of some main components such as curing agents, solid components, initiators, solvents. Catalysts and initiators such as peroxides shall be stored separately.

b) Shelf Life

The properties of uncured resin could change with time and/or with temperature variation or humidity, these conditions can affect its properties and reactivity. Manufacturers should specify shelf life during which the properties of the resin materials will not be altered and continue to meet the specified performance. Materials exceeding recommended shelf life are unsuitable for use and could be toxic. Disposal of expired materials shall be carried out according to specified manner set by the manufacturer and according to national and/or international laws and standards.

2.4.1.3 Handling

a) Material Safety Information

FRP material safety information shall be obtained from manufacturers, and shall be kept available at job sites.

b) Information Sources

Detailed information with respect to handling and hazards of FRP material components can be obtained from manufacturers' materials reports and relevant standards.

c) General Handling Risks

Thermoset resins represent a general group of product that includes unsaturated polyesters, vinyl-esters, epoxies, and polyurethane resins. The materials used with them can be described as hardeners, curing compounds, peroxide initiators, fillers and flexibility materials.

There are handling precautions that shall be followed when dealing with thermoset resins and its components. The following is a list of the risks that could be encountered when handling thermoset resins:

1- Skin irritation or inflammation such as; burns and rash.
2- Skin allergic reaction similar to that experienced with building insulation materials such as glass wool.
3- Exposure to organic vapors from cleaning solvents or monomers or diluted solutions.
4- High concentration in air could lead to exposure or fire of flammable materials when exposed to high temperature or flame or sparks or static electricity or any source of ignition.
5- Exposure to fire and injury of personal when exposed to the reactions due to bad storage.
6- Exposure to hazard dust from grinding and handling of cured FRP.

The availability of handling precautions and regulations are essential due to the complexity of thermoset resin chemical composition and the associated material. These labels shall be easily read and understood by any personal dealing with such materials. National and/or international rules and regulations shall be consulted in that respect.

d) Personal Safety and Clothing during Handling

Disposable plastic or rubber clothing and gloves are considered the most suitable and recommended for use during the handling of fibers and resins. Gloves shall be resistant to resins and solvents. Safety eye glasses should be used when handling resins and solvents. Gas masks shall be used for protection from vapor and hazard dust to protect the respiratory system.

e) Safety of Handling Area

Working area shall be well ventilated and surfaces shall be protected from the contamination and spills of resins. Each FRP constituent materials require special handling and storage requirements. Manufacturers shall be consulted to obtain the necessary information, precautions, safety regulations that shall be followed in handling areas for each FRP constituent materials.

The danger of some resins is in mixing its components, which is why reading product data sheet before use is essential to get to know the proper mixing procedure and the handling risks.

Curing of resins is accompanied with increasing the temperature which in turn accelerates the reaction. Uncontrolled reactions could lead to fires or smoke or extensive boiling in mixing containers, therefore, it shall be carefully monitored.

f) Cleaning and Trash Disposal

Cleaning processes includes the use of solvents, which are flammable materials, thus caution should be experienced. Solvents differ in its flammability. In all cases the resulting trash shall be collected and disposed according to specified way set by environmental authorities.

2.4.2 Shipment, Storage and Handling of FRP Bars

2.4.2.1 Handling and Storage of Bars

FRP bars are more susceptible to its surface damage. Damage or cracking of the surface of FRP bars will result in significantly reducing its strength. Also, it will result in reducing its durability because of the ease with which alkalis can penetrate through the bars and damage the fibers. The following precautions shall be followed to reduce the damage to the FRP bars and the risk to the personal dealing with it:

- Wearing gloves when handling the FRP bars to avoid personal injuries that could result from the sharp edged bars or exposed fibers.
- FRP bars should be stored on special shelves and not on the ground to avoid contamination and to facilitate its handling.
- FRP bars shall be protected from exposure to high temperature, ultra violet rays and chemicals for its harmful effect on bars.
- The FRP bars could get contaminated with materials such as form releasing agents that could significantly reduce the bond with concrete, bars shall be cleaned with special solvents that shall not affect the bars properties before its use.

- It may be necessary to use separator bars to reduce any bending in the FRP bars.
- Safety masks, eye glasses and gloves shall be used when cutting FRP bars.
- Cutting of FRP bars should be done using very high speed cutting saw.
- FRP bars shall not be sheared during transportation, storage, handling and cutting.

2.4.2.2 Placement and Assembly

Generally, FRP bars are placed and assembled similar to steel reinforcement. Special precautions should be considered as follows:

1- FRP bars shall be placed and assembled using chairs which shall not cause any damage to the bars (preferred to be from plastics or any non-corrosive materials), the specifications for the chairs shall be stated in the project specifications.
2- Bars shall be securely placed and no displacement shall be allowed during concrete casting. FRP bars could be secured in its place using any coated tie wire or plastic wires. Project specifications shall include the requirements of the tying method and material.
3- FRP bars manufactured from thermoset resin are not allowed to be bent on site. Manufacturer's specifications shall be followed.
4- Continuity of bars shall be achieved using overlap splices, the length of the lap and type splice depends on concrete grade, grade of bar, its size, shape surface texture, distance between bars and the concrete cover.
5- Structural detailed drawing for lap splices shall be included in the project specifications.

2.5 Inspection, Evaluation and Acceptance of FRP Systems

FRP manufacturers, contractors and any personals working in this field shall apply quality control and quality assurance procedures. The quality control procedure shall be comprehensive to all project fields and aspects. The degree of quality control, frequency of testing and number of tests depends on the project size and importance. Quality control could be carried out by several inspection procedures and testing to document the acceptance of the materials during the various construction steps.

2.5.1 Inspection

The application of FRP systems shall be inspected during all its application phases according to code's requirements which are given in Section 4.4 in Chapter 4. In case on the unavailability of such requirements, inspection shall be carried out by a certified quality controller engineer with experience in this field and aware of the design charts and project specifications.

2.5.2 Evaluation and Acceptance

FRP systems shall be evaluated and accepted according to its compliance with specifications and design drawings. Evaluation processes and acceptance criteria are set in Sections 4.4.3.6, 4.4.3.7 and 4.4.3.8 in Chapter 4.

2.5.2.1 Materials

Before the commencement of any project, the manufacturer of the FRP system shall supply all the necessary documents for the properties of materials and test results and its compliance with specifications. Additional tests could be conducted to assure the reported properties if necessary and depending on the project size and importance.

Witnessed specimens shall be used to evaluate tensile strength, modulus of elasticity, overlap splice strength, and hardness of FRP manufactured and cured on site. Manufacturing and curing shall follow the procedures outlined in the project specifications. FRP panels with various dimensions and thicknesses manufactured and cured on site according to the assemblage plan shall be tested in the laboratory. Witnessed specimens should be retained or delivered frequently, according to quality control plan, to an approved laboratory for testing of tensile strength, stiffness, and infra-red spectrometer analysis. Tensile strength and modulus of elasticity for FRP constituent materials shall be conducted according to international specifications and project specifications. This code includes the properties that should be tested and determined such as; tensile strength, modulus of elasticity, thermal analysis…etc. In some FRP systems it is difficult to manufacture small panels, such as the case of pre-cured systems or machine shaped systems, in this situation witness panels should be modified by the engineer to accommodate the required testing. Tensile strength, modulus of elasticity and bond strength of overlap splices could be determined using special testing on specimens manufactured on site or during assembling. Sample cups of mixed resin shall be prepared according to predetermined sampling plan to determine the curing level.

2.5.2.2 Fiber Orientation

Fibers and laminate orientation for pre-cured FRP shall be evaluated by visual inspection. During the application of FRP using wet lay-up technique, the waviness of fibers (localized deviation from straight fiber line in form of kinks or waves) shall be evaluated and quantified. Any deviations more than 5 degrees than the fiber orientation determined in design charts shall be reported to the engineer.

2.5.2.3 Delamination

Cured FRP systems shall be evaluated with respect to delamination and air voids between plies or between FRP system and concrete according the procedure detailed in Section 4.4.3.9 in Chapter 4.

Repair of FRP delamination shall be carried out and evaluated according to the engineer's directions. After the completion of repair processes re-inspection of the laminates shall be carried out to ensure the quality.

2.5.2.4 Curing Process of Resins

Evaluation of curing process of FRP systems shall be determined through laboratory tests on witness panels or resin samples as described in Section 4.4.3.7.4 in Chapter 4.

2.5.2.5 Adhesion

Tensile strength for adhesion materials, which are used in the application of FRP systems that depends on adhesion, shall be conducted according to that detailed in Section 4.4.1.3.1 in Chapter 4.

2.5.2.6 Thickness of Cured Material

The thickness of the FRP system or laminate shall be determined as described in Section 4.4.3.8.5 in Chapter 4.

2.5.3 Quality Control and Inspection of FRP Bars

Quality control on FRP bars shall be carried out through testing specimens from each consignment separately. Test results submitted by the manufacturer could be relied on in acceptance and additional tests should be carried out on FRP bars after is delivery in approved laboratory. Testing shall be conducted according to the procedures described in any international code of practice or specifications or those stated in the project specifications.

The following tests shall be conducted at least once before and after changing the supplier or changing the manufacturing process or changing any constituent of the FRP bar:

1- Axial tensile strength of FRP bars.
2- Bond strength of FRP bars by pull-out test.
3- Alkali resistance of FRP bars.

The following tests shall be carried out for quality control during the supply of FRP bars:

1- Tensile strength
2- Modulus of elasticity in tension and maximum strain

The manufacturer shall supply, upon request, a certificate of compliance of any FRP bars consignment with full description of conducted tests.

Note: Testing could be carried out according to test procedures detailed in the appendix 2 (FRP tests).

CHAPTER 3

DURABILITY OF FIBER REINFORCED POLYMERS (FRP)

3.1. General Considerations

Durability of the FRP system is to be evaluated; according to its capacity to resist external environmental factors while maintaining its efficiency in the presence of external environmental conditions.

This chapter focuses on the materials and systems of which the specifications and application rules are mentioned in chapters two and four from this code. However, in case of using any material other than the ones mentioned before, its specifications and durability must be studied before use.

This chapter consists of the following sections:

a) Introducing the durability of FRP and the binding materials and demonstrating the influential factors. It also includes the basis that are to be taken into consideration if FRP is subjected to moisture, chemicals specially alcohols, elevated temperatures, freezing and thawing, and ultra violet rays (sections 3.5.2,3,4,5 & 6).
b) Fire resistance of the structures strengthened by FRP (section 3.5.7).
c) Creep and fatigue specifications (sections 3.8 & 10).

3.2. Definition of FRP Durability

It is the ability of FRP to resist the surrounding environmental factors; moisture, temperature, dryness and damping cycles, freezing and thawing cycles, Ultra Violet rays and other factors like chemical attack, alkaline environment of concrete, creep, stress relief, fatigue and fire along the age of the structure. Incase FRP is subjected to any of the above mentioned factors separately or more than one together, they will have a negative effect on its mechanical, physical or chemical properties by time.

3.3. Durability of Epoxy Binding Materials

3.3.1. General

This part focuses on the durability of the epoxy resin that is used as a binding material for the FRP systems used in strengthening concrete structural elements. It also handles the factors influencing the durability of the epoxy resin and the rules to be followed in order to obtain a safe structure. The durability of the epoxy resin depends on the durability of the strengthened concrete surface as well as other factors like environmental factors and method of preparing, handling and curing the epoxy resin.

3.3.2. Humidity Effect

a) The long time exposure of moisture on the epoxy resins has negative impacts on the properties and resistance of the epoxy resin as the time of exposure to moisture increases.
b) Resistance of the binding decreases by a huge extent when certain types of epoxies are subjected to static loading in the presence of moisture.
c) Epoxy resins are not supposed to be used as binding materials if the strengthened concrete surface is moist or wet, unless the epoxy is specially prepared for this purpose as shown in (section 4.4.1.2).
d) Water vapor exits must be allowed for outside the concrete surface in applications where water movement is expected inside the concrete as shown in (section 4.3.2.4.8).

3.3.3. Freezing and Thawing Effect

a) Freezing and thawing cycles for the water results in partial loss of the binding resistance either between the FRP system and the concrete surface or between the FRP layers themselves. The resistance decreases as a result of the gaps created between the binding material and the concrete.
b) The presence of salts accelerates the deterioration of the binding resistance due to the formation and size of the salt crystals formed

3.3.4. Acidic and Alkaline Environment Effect

a) Epoxy resin showed acceptable results when generally subjected to chemicals specially acids and alcohols. The effect of the epoxy resins by these chemicals mainly depends on their concentration and the temperature. Table 3.1 shows values for such effects.
b) Incase of using the resin in structures subjected to one of those environments, a resin with resistance to those environments must be used.
c) Tests must be performed to insure the suitability of the epoxy resin with the surrounding environment.

3.3.5. Radiation Effect

Epoxy resins showed high resistance to radiations specially gamma radiations.

3.3.6. Temperature Effect

a)The effect of temperature on the properties of the epoxy resin can be neglected as long as the temperature is less that (HDT), at which the properties of the epoxy resin are negatively affected; strength, resistance, creep, and chemicals effect.

b)Most of the resins expand and evaporate at elevated temperatures exceeding 300°C and the resulting smokes at this temperature could have a poisonous effect.

3.3.7. Creep Effect

An epoxy resin creeps either in normal or elevated temperatures and this depends on the HDT temperature and the effective stress. Creep rate increases with the increase of the temperature beyond the HDT.

3.4. Durability of Fibers

a-This section focuses on the durability of the fibers alone. Taking into consideration that the fibers are never in direct contact with the surrounding environmental factors because the resin used to form the FRP matrix is the material that is in direct contact with the surrounding factors.

b-Generally carbon fibers show good durability in different medias since it does not swallow water and has high resistance to chemicals, acids, alcohols and solvents. However, it shall be taken into consideration that carbon fiber is a good conductor of electricity which may result in expediting rust in steel if placed close to it or in contact with it.

c-Aramid fibers are highly affected by moisture especially in the presence of high percentage of moisture. It has low resistance to Ultra Violet rays and needs protection against it. Elevated temperatures have a big negative impact on the aramid fibers.

d-Durability of glass fibers differs according to the kind of glass fibers used. AR glass shows good resistance to alcohols whereas E&S glass show poor resistance. As for acids, glass fibers are negatively affected by them.

3.5. Soundness of FRP Matrix

3.5.1. Moisture soundness ofFRP Matrix

a)Humidity affects FRP which results in the increase in weight of the, materials.

b- The rate of absorbing humidity of these materials depends on the surrounding temperature, the stress applied on it as well as the time of exposure to humidity, and the components and properties of the materials.

c- Glass and aramid fibers are more affected by humidity.

d- Absorbing humidity results in extra residual stresses as well as in resins which increases the rate of creep.

e- Aramid FRP is avoided in environments with high humidity.

f- Sufficient protection shall be accounted for when using glass FRP in humid environments as in accordance with (section 3.5.11.2)

In the coming sections mutual effect of humidity and other factors will be discussed.

3.5.2. Chemicals soundness of FRP Matrix

3.5.2.1.General

This section focuses on the durability of FRP when subjected to chemical attacks depending on the kind, concentration and the cycles that the system is subjected to as well as the state of the chemicals; solid, liquid or gaseous state. This section also focuses on the measures that are to be taken to resist the harmful chemical effects. It should be noted also that the effect of the chemicals on the fibers and resins separately is different than its effect on the system as a whole. This effect differs based on the rate of spreading and absorption of the chemicals inside the FRP system and the resin used. The scope of this section also covers the effect of the acids and solvents on the FRP system.

3.5.2.2. Salts Effect on the Durability of FRP Matrix

a) This section handles the effect of different salts on the durability of the FRP system which may result in doubling the effect.

b) The presence of soluble salts results in an increase in the osmosis property which drives salty solvent to move inside the FRP system which has a negative impact on the durability of the system.

c) Durability of the FRP system depends on the type of resin used and epoxy is considered to be the best resin in resisting different types of salts while vinyl aster better resists chloride salts that polyester. Generally, resins resistance to salts is acceptable.

d) The kind of salt and its concentration affect the FRP system and the concentration that results in obvious weakness of the system shall be indicated and this is by means of laboratory testing.

e) Carbon FRP systems show the best resistance to salts. It is better than Glass and Aramid FRP systems.

3.5.2.3. Acids and Solvents Effect on the Durability of FRP Matrix

a) Nitric, hydrochloric acids affect most of the FRP systems. The degree by which the system is affected depends on the kind of acids, its concentration, the surrounding temperature and the type of resin used.

b) Carbon FRP shows better resistance to acids than other reinforcing fibers such as glass and Aramid.

c) The increase in temperature accelerates the deterioration of the FRP system subjected to acids.

d) Generally FRP resist solvents such as benzene and kerosene where GFRP is slightly affected.

3.5.2.4. Alkaline Effect on the Durability of FRP Matrix

a) Weak alkaline environment ($7<pH< 10$) and strong ($pH>10$) have negative impacts on the properties of GFRP.

b) When GFRP is subjected to highly alkaline environment, a severe drop in the mechanical properties of the system occurs which may exceed 70% which may result in the total damage of the system.

c) Some GFRP systems that have resistance to alkaline environments can be used if there are authorized lab tests indicating its adequacy as well as there must be experience in the method of application in similar projects.

d) The effect of the alkaline environment can be totally neglected when using Carbon fiber reinforced polymer (CFRP)

e) Aramid fiber reinforced polymer, (AFRP) systems show acceptable resistance to the alkaline environment. It comes in the second place after CFRP systems

f) Alkaline environments could result in extra bonding between the FRP bars reinforcing the concrete and this is due to the slight expansion in the size of the bars.

3.5.3. Temperature Effect on the Durability of FRP Matrix

3.5.3.1.General

Temperature of the surrounding environment of the FRP system has a direct effect on the properties of the FRP system and this is for high and low temperatures. This section will deal with mentioned effects as well as temperature effects with humidity effects

3.5.3.2. Elevated Temperatures Effect

a) There are no obvious effects of the temperature surrounding the structure on the FRP system if it is below the glass transition temperature. However, if it is higher than the glass transition temperature then the effect depends on:

b) Type of resin used in the FRP system.

c) Type of the resin used as a binding material.

d) Type of fibers used and their direction and whether the system is internal or external.

e) Materials in the matrix are subjected to different cycles of temperature changes.
f) Type of cover and protection material
g) When using certain types of FRP systems that have a relatively high expansion rate, the changes in the temperature can result in tension stresses in the concrete surrounding the bars, which afterwards results in cracks in the concrete that decrease the concrete resistance. The designer shall take into consideration those stresses.
h) In cases where the structure might be subjected to temperatures close to or slightly higher than the glass transition temperature the designer shall take into consideration the reduction in elasticity and strength.
i) The effect of the temperatures below the glass transition temperature could be neglected when accounting for the connection between the concrete surface and the externally bonded FRP system.
j) An effective protection system must be designed for the structure incase it is subjected to glass transition temperature or higher.
k) The designer shall take into consideration the effect of the increase in the surrounding temperature on the increase in creep and stress relief.
l) The increase in temperature results in the increase of the rate of humidity absorption which expedites the humidity negative impacts on the FRP system. This is why the designer must choose the suitable resin for the dual effect and this is according to table (3-1). It is advisable to use epoxy in such cases on the condition that it was tested before in such conditions.
m) Protective measures shall be accounted for incase of increase of the surrounding temperature together with the subjection of the FRP system to chemical solvents or alkaline environments because high temperatures expedite the negative effects of the aforementioned environments. Table (3-1) shows the effect of different temperatures (25°C and 65°C) on the behavior of resins or epoxies in different environments.
i) It is advisable to use the minimum thickness of the epoxy resin specified by the manufacturer for binding FRP sheets to the concrete surface to decrease the high thermal expansion rate of the epoxy resin

3.5.3.3.Ultimate Temperature

a)The ultimate temperature for the FRP system shall be determined; either if the system is internal or external. The ultimate temperature is the maximum temperature at which the system operates safely without loosing any mechanical properties. This temperature is equal to 20°C less than the glass transition temperature.

b)It is allowable to exceed the ultimate temperature if there is a protection system available for the FRP system. The protection system must be applied by experts and must have authorized tests that assure the adequacy of the system. However, temperature shall not exceed the glass transition temperature.

3.5.4. Freezing and Thawing Cyclic Effect on the Durability of FRP Matrix

a) Temperatures below 0°C and the freezing and thawing cycles do not affect the carbon and glass fibers, but they affect the resin and the binding material and the FRP system as a whole.

b) The resin of the system and the binding polymeric material is converted into a brittle material which results in the decrease of at temperatures below 0°C.

c) It shall be taken into consideration that by the decrease in temperature surrounding some types of epoxies, their ability to absorb water increases and this is what is known by "reverse temperature effect phenomenon".

d) Freezing and thawing cycles might result in partial loss of the bond in the FRP system itself especially if there are gaps in between the bonding levels. This loss may reach 20% if Aramid FRP internal system is used.

e) Consecutive freezing and thawing cycles could result in a reduction in the ultimate tension resistance as well as the elasticity of the FRP system. Deterioration increases in the mechanical properties along with the freezing and thawing cycles due to the generation of small cracks in the resin. The negative effect of these cracks depends on the value of the contraction resulting from the curing of the resin.

f) The freezing and thawing cycles could result in further deterioration in the presence of salts in a damp or wet environment and this is due to the generation of critical cracks and gradual deterioration resulting from the formation of crystals and salts concentration.

g) Residual stresses shall be measured if the FRP system is subjected to a huge difference between the curing temperature and the temperature in the cold environment. To overcome the residual stresses the system can be placed in a temperature as high as 93°c.

h) When using fibers in an environment subject to freezing and thawing, precautions shall be made in selecting the binding material so as not to be deteriorated and converted to a brittle material. In all cases, there must be experienced and authorized lab tests insuring the quality and safety of the materials.
i) Aramid fibers must not be used in applications subject to freezing and thawing.
j) Surface preparation shall be done properly, keeping it as smooth as possible in order to avoid gaps between the FRP system and the strengthened concrete surface and allowing for perfect adhesion.

3.5.5. Ultra- Violet Rays (U.V.) Effect on the Durability of FRP Matrix

a) Ultra violet rays have negative impacts on the FRP system since it causes a breakdown in the chemical chain which might result in reaction of the materials with oxygen and thus oxidizing them.
b) The negative impact is limited to the fibers directly subjected to the U.V. rays.
c) One of the main negative impacts is that the surface damaged by the U.V. rays has higher capacity of absorbing humidity which affects the material internally.
d) Tests have proved that U.V. rays highly affect Aramid fibers, have a lower effect on glass fibers and do not affect carbon fibers.
e) Fibers shall be stored away from the sun.
f) Protection of fibers affected by UV rays shall be done according to (section 3.5.11.3)

3.5.6. Radiations Effect on the Durability of FRP Matrix

There is no enough data on the durability of the FRP system subjected to radiations. However, epoxy showed good durability when subjected to radiations especially gamma radiations.

3.5.7. Fire Capacity ofFRP Matrix

a)When the temperature exceeds the glass transition temperature, resins start becoming elastic. At the temperatures of fire, the surface layers start to reduce to ashes. The advantage of polymers is that when they reach that point they become self extinguishable.

b)Fire resistance depends on the properties of insulation and the thermal transmission of the binding material as well as the degree and exposure time and the thermal effect on the binding layer.

c)FRP systems exposed to fire loose all of its abilities. However, resistance to fire can be enhanced by adding materials especially for fire resistance and adding protection layers like cement mortar and sand with a suitable thickness or like very soft clay or adding aluminum hydrates in the resin itself. If any of these materials are added they shall be taken into consideration when accounting for the overall system's resistance to fire.

3.5.8. Creep in FRP

3.5.8.1.General

FRP system subject to static loading by time resulting from dead and live loads loaded on it results in rupture at a certain point in time (Creep Rupture Time). The increase in tensile stresses on the FRP system decreases the creep rupture time. Creep rupture time also decreases due to the bad surrounding environmental conditions like the increase in temperature, being exposed to U.V. rays, high alcoholic environments, cycles of dryness and damping and freezing and thawing cycles. Generally CFRP systems is the least exposed to creep rupture followed by AFRP and finally the GFRP.

3.5.8.2.Creep Limit

a) Creep limit is the maximum stress allowed for FRP systems under static loading (dead loads + part of live loads that are permanent). Creep limit protects the structure from creep rupture. Creep limit depends on the type of fibers used and is taken as follows:

Glass Fibers	$Cl = 0.20\ f_{fu}$	(3-1)
Aramid Fibers	$Cl = 0.30\ f_{fu}$	(3-2)
Carbon Fibers	$C_l = 0.55\ f_{fu}$	(3-3)

Where , f_{fu} represents the tensile strength of the FRP.

b) Calculated stresses on the FRP system under permanent service loading are not supposed to exceed the creep limit.

3.5.9. Reduction factors for the Ultimate Strength and Ultimate Strain for Various Environmental Exposure Conditions

a) The surrounding conditions of the structural element have direct effect on the FRP system.
b) The extent of the effect of the surrounding environment depends on the type of fibers, polymers and the type and concentration of the polymeric matrix used. In addition to, the extent at which the surface of the FRP system is exposed.

c) The severe environmental conditions reduce the creep rupture time. This is why the ultimate strength of the section enhanced by FRP shall be calculated and the ultimate tensile strength and the ultimate strain shall be reduced according to equations (3-4) and (3-5).

d) The modulus of elasticity is taken as is because it is not affected by the surrounding environment and is calculated as shown in equation (3-6).

$$f_{fu}^* = \quad f_{fu} \qquad (3\text{-}4)$$

$$\varepsilon_{fu}^* = \quad CE \quad \varepsilon_{fu} \qquad (3\text{-}5)$$

$$E_f = f_{fu} \quad \varepsilon_{fu} \qquad (3\text{-}6)$$

Where, f_{fu}^* : Ultimate tensile strength

ε_{fu}^* : Ultimate strain

CE : Environmental reduction factor

E_f : Modulus of elasticity

Table (3-2) Environmental Reduction Factor

Degree of surface exposure to environmental factors	Fiber type/ binding resin	CE
Protected Surfaces (includes all the factors)	Carbon / Epoxy	0.95
	Aramid / Epoxy	0.85
	Glass / Epoxy	0.75
Unprotected surfaces(includes bridges. and all the elements exposed to the environment)	Carbon / Epoxy	0.85
	Aramid / Epoxy	0.75
	Glass / Epoxy	0.65
Surfaces exposed to harmful environments (include sewage plants. chemical factories and all the surfaces exposed to chemicals or	Carbon / Epoxy	0.85
	Aramid / Epoxy	0.70
	Glass / Epoxy	0.50

e)If the FRP system is exposed to high temperature, the C E factor must be reduced based on lab experiments.

f)If the FRP system is in an inactive environment (internal use) then higher CE factors could be used. However, if it is in an active environment like an environment with high temperature, high humidity, salty water or alkaline nature then lower CE factor should be used. Lab experimental tests should guarantee the use of higher CE values for protection against active environments.

3.5.10. Fatigue

a)Carbon fibers are the least affected by fatigue when compared to other fibers and reinforcing steel bars. The fatigue limit is taken for the CFRP systems with unidirectional fibers to be 60 % of the ultimate tensile strength and this is when using fibers that constitute 60% of the size of the CFRP system and is subjected to average tension (percentage from maximum to minimum stress is 10%). Carbon fibers strength is not affected by fatigue under humidity or the surrounding temperature if the resin and the binding material between the CFRP system and concrete are not affected.

b)Fatigue limit for glass fibers is 30% and for aramid fibers is 55% of the ultimate tensile strength which is less than the fatigue limit of the carbon fibers under the same loading conditions.

c)If the average between the minimum to maximum stress increases beyond 10% or the size of the fibers is less than 60% then lab tests must be performed to determine the fatigue limit.

d)It must be taken into consideration that environmental factors like humidity and high temperature have negative impacts on the fatigue limit of the glass and aramid fibers. Lab tests should be performed in such cases to determine the fatigue limit.

3.5.11. Protective Layers for FRP

3.5.11.1. General

The design engineer shall make sure that the protection system is properly applied to protect the FRP systems from the different environmental factors. The FRP system shall resist humidity, chemicals and U.V. rays and this will be through using the proper protection system. This part focuses on the protection of the FRP system from humidity, chemicals, U.V. rays, thunder storms and steel corrosion by means of galvanic cells.

3.5.11.2. Protection against Moisture and Chemicals

Protection of GFRP systems is generally desired to protect against humidity and other harmful materials by using protective layers like urethane, epoxy or some kinds of latex.

3.5.11.3. Protection against Ultra Violet Rays

a)Most of the standards specified for FRP systems require special coating for protections against U.V. rays. Protections is done by using acrylic coating, poly urethane coating, gel or fluorine with a resin base and a minimum of two coats is required.

b)Guidance from the transportation department in California in the United States of America could be acquired regarding the coats used for protection against U.V. rays.

3.5.11.4. Galvanic cell protection

a) Many of the FRP system applications are not exposed to lightening like applications inside buildings or. However, if the system is likely to be exposed to lightening then it should be protected by a metal mesh.
b) To protect the reinforcing steel bars from corrosion resulting from the galvanic corrosion cells, carbon fibers must not be in contact with steel and this is done by good monitoring and quality control.

3.5.11.5. Conditions for using Protection Layers

Protective layers are applied after the whole FRP system is applied on the concrete. It is the last step in the process. However, some precautions are required:

a) Protection layers shall not be applied before the binding epoxy resin cures and strengthens.
b) The surface to be protected must be clean and free from dust. It shall be cleaned by a brush or a dry cloth to prevent any scratches.
c) The surface shall be free from moist, oils or any material that will hinder the binding process of the protective layers to it.
d) Polymers that will be used for protection shall be properly selected to suit the site temperature.
e) Materials with lapsed expiry dates shall not be used.
f) Any polymers or epoxies that their pot life has expired shall not be used.

TABLE 3-1 Effect of Chemicals on the Properties of Various Types of Resins for Temperatures of $25^{o\,C}$ and 65^{o} C

Solvents	Acrylic		Epoxy		Polyester		Polyrethane		Silicon		Estrine p
	25°C	65°C	25°C	65°C	25°C	65°C	25°C	65°C	25°C	65°C	25°C
Unoxidized Acids	Acceptable	Not Clear	Acceptable	Acceptable	Not Clear	Not Clear	Not Clear		Not Cl	Not Clear	Acceptable
Oxidized Acids	Weak										
Strano Salty Solvents	Acceptable										
Strano Alcohols	Acceptable	Not Clear	Acceptable	Acceptable	Weak	Weak	Not Clear	Weak	Acceptab	Not Clear	Acceptable
	Acceptable	Not Clear	Acceptable	Acceptable	Not Clear	Weak	Weak	Weak	Acceptab	Acceptable	Acceptable
	Weak	Weak	Acceptable	Not Clear	Weak	Weak	Not Clear	Weak	Not Clear	Weak	Weak
Water	Acceptable					Not Clear	Acceptable				

CHAPTER 4

REPAIR AND STRENGTHENING OF REINFORCED CONCRETE STRUCTURES USING FIBER REINFORCED POLYMER, (FRP)

GENERAL CONSIDERATIONS:

In this Chapter, provisions for the design and installation of FRP systems used in the strengthening and repair of concrete structures are presented. The FRP systems considered are limited to those outlined in this chapter using the material properties given in Chapter 2. The design provisions for the FRP strengthened structures are based on the Limit States Design Method outlined in part 3 of this chapter, with due considerations of the adverse environmental effects on FRP strengthening and repair works outlined in Chapter 3 . The strengthening and repair applications considered in this chapter are limited only to the cases of externally bonded FRP laminates and sheets to the concrete elements.

This chapter comprises the following four parts:

PART 1 4.1: STRUCTURAL ASSESSMENT, CONDITION SURVEY, AND STRENGTHENING DEMANDS

This part is concerned with providing brief information for the probable causes of the deterioration and distress of concrete structures, (Section 4-1-3), and to presenting general guidance for carrying out condition survey and structural evaluation, along with the assessment of strengthening demands of existing structures, (Section 4-1-4).

PART 2 4.2: BASES FOR THE CHOICE OF REPAIR AND STRENGTHENING MATERIALS AND SYSTEMS

This part provides guidance for the selection of FRP materials and systems for externally strengthening concrete structures (section 4-2-2). Such Applications can be categorized as either bond-critical or contact-critical applications, as outlined in section 4-2-3. This part also provides information pertaining to the various strengthening systems utilizing FRP composites (section 4-2-4), along with guidance for the selection of suitable FRP systems for particular applications, as outlined in section 4-2-5.

PART 3 4.3: LIMIT STATES DESIGN METHOD

This part provides information pertaining to the Limit States Design method for strengthening structures using FRP. In section 4-3-1 the general design consideration and philosophy along with strengthening limits are presented. In section 4-3-2 Limit States Design method is outlined. The

Flexural Strengthening is presented in 4-3-2-1 while shear and torsion strengthening are given in section 4-3-2-2. The strengthening of members subject to either compressive or tensile forces is given in section 4-3-2-3. In Section 4-3-3 the serviceability considerations for FRP strengthened structures are presented.

PART 4: 4-4 APPLICATION REQUIREMENTS FOR REPAIR AND STRENGTHENING WORKS

This part provides information pertaining to the Installation requirements of FRP works (section 4.4.1), qualification of contractor (section 4-4-2), inspection, evaluation, acceptance and quality control, (section 4-4-3), as well as maintenance, observation and repair of strengthening work using FRP, (section 4.4.4)

PART 1

4.1: STRUCTURAL ASSESSMENT, CONDITION SURVEY,AND STRENGTHENING DEMANDS

4.1.1 GENERAL

Condition assessment and the evaluation of the strengthening demands of existing structures shall be carried out with due consideration of the following:

a- The probable causes of structural defects.

b-The structural safety, serviceability and durability requirements of the Egyptian code for concrete structures, ECP 203. The condition assessment shall be based on a through structural analysis, field and laboratory tests and the project’s specifications.

c- The methods of strengthening and repair to be employed.

The preceding works shall be performed by professional engineers with experience in the appropriate field of structural engineering related to such works. Also the construction of such works shall be carried out by certified contractors with extensive experience in repair and strengthening works.

4.1.2 TECHNICAL TERMS

Technical terms are usually used in matters pertaining to FRP works; namely, Restorations, Rehabilitation, Strengthening, Repair and Retrofitting

4.1.3 PROBABLE CAUSES OF STRUCTURAL DEFECTS

In this section, a summary of the probable causes of structural defects of concrete structures are presented.

4.1.3.1 Probable Structural Defects

The structural defects can be classified as follows:

- **Overall structural defects that can adversely affect the safety, serviceability and ultimate strength of the structure**:

  This include but are not limited to partial or total collapse of the main structural elements, structural instability, sliding, even and differential settlements , and concrete cracking .

- **Structural elements defects:**

  This include all types of deterioration and distress of the various structural elements such as cracking, corrosion, excessive deformations, bucking of columns, loss of concrete cover, and localized structural failures of structural elements.

4.1.3.2 CAUSES OF DEFECTS OF CONCRETE STRUCTURES

The causes of defects of concrete structures can be attributed to a number of reasons which include but are not limited to the following:

- Soil problems
- Lack of proper structural detailing
- The use of defective materials
- Construction errors
- Lack of maintenance
- Modification of configurations, and elements of the structure
- Natural disastrous.

The condition assessment of the structure shall consider such adverse effects either separately or in combinations thereof.

4.1.4 STRUCTURAL EVALUATION AND STRENGTHENING DEMANDS

Structural evaluation shall be performed on the bases of a through analysis of the structure using the information obtained from field and laboratory tests. The types of tests are determined according to the extent and nature of the structural defects. The findings of the structural assessment shall be presented in structural assessment reports. Such reports shall assess the safety of the structure and shall also indicate the types and extents of defects of the various elements of the structure if any. For such defective elements, recommendation regarding the alternate methods for strengthening and repair along with comparisons between these methods from both technical and economical standpoints shall be needed. In some cases it may be advisable to demolish of the structure either partially or totally. Recommendations to that effect must be clearly indicated with justifications.

4.1.4.1 Structural Information

All information about the structure that can be used in the condition assessment must be obtained.

4.1.4.2- Visual Inspection

A preliminary comprehensive visual inspection for the entire structure and elements thereof at the various floors levels shall be performed along with a number of field tests upon which the preliminary probable causes of the structural defects can be determined. Recommendations regarding the types and locations of the field tests needed for the comprehensive condition survey can then be made.

4.1.4.3 Condition Survey and Tests

Field and laboratory tests form the bases upon which a comprehensive condition survey for the structure can be prepared. Such tests include but are not limited to non-destructive tests, core tests, chemical analysis tests, carbonation tests of concrete. Depending on the nature of the problem, other types of tests may needed including health monitoring of the structure, load tests and soil investigation and foundation tests.

4.1.4.4 Analysis of Structure

a- A through analysis for the existing structure in its defective condition shall be carried out. The analysis shall take into consideration the presence and extents of concrete cracks, reinforcing steel corrosions, and the partial or total loss of any structural elements and the resulting redistribution of loads. The strength evaluation of the structural elements shall be carried out in accordance with the Egyptian code for concrete structures, ECP203, upon which the strengthening demands of the distressed elements can be assessed

b- Prior to the implementation of strengthening works, the structure shall be reanalyzed taking into consideration the changes in the structural elements resulting from the proposed strengthening and repair works and the effects of such works on the distribution of loads. The resulting structure shall satisfy the strength and serviceability requirements of the Egyptian code for concrete structures, ECP203.

4.1.4.5- Strengthening Demands

The strengthening demands can be assessed on the bases of the results of the through analysis of the structure in its distressed condition. Comparison between all suitable methods of strengthening must be performed in order to determine the most suitable strengthening method to use.

4.1.4.6- Structural Assessment Report

Structural assessment reports are prepared based on the visual inspection of the structure and after carrying out field and laboratory tests, a complete analysis of the structure as per section 4-1-4-4, along with strength and serviceability assessments of the structure in accordance with the Egyptian Code for concrete structures, ECP203. The report shall contain complete information about all distressed elements of the structure and shall provide recommendations regarding the strengthening demands of the distressed elements and the recommended methods for strengthening such elements.

PART 2
4.2 : CHOICE OF REPAIR AND STRENGTHENING MATERIALS AND TECHNIQUES

4.2.1 General

This part provides general information on the selections of FRP materials and systems for use in concrete strengthening .

The materials and systems usually employed in the strengthening of concrete structures can be categorized as either traditional systems in the form of the use steel plate bonding , section enlargement and external post-tensioning, or advanced systems using fiber reinforced composites, as well as, combinations between the traditional and advanced systems referred to as hybrid systems

The selection of the strengthening method for particular applications is a critical process. While FRP systems are ideally suited for use in certain types of applications, it may not be practical use FRP systems for other types of strengthening applications from both technical and economical standpoints. These cases include but are not limited to, structures exposed to highly aggressive environment and fire that can adversely affect the effeciency of FRP systems and the time dependent performance of the FRP strengthened structure. In addition, the cases where the strengthening limits specified in the FRP code will not enable the use of FRP systems for certain strengthening applications. For such cases traditional and hybrid techniques will be more appropriate to use

For the cases where FRP systems are suitable to use, comparision between the various systems shall be performed, as follows:

I - Choice of FRP materials : The choice of FRP materials for a particular application is based on the choice of the mechnical, physical and chemical properties of the materials **as** given in chapter 2, with due consederation of the durability requirements of chapter 3.

II- Choice of FRP systems : Only integreal systems that are certified by the suppliers can be used for concrerte strengthenings. Combining fibers and resins obtained from different sources is not permited. The choice of an FRP system for a particular application is governed by a number of considerations, as follows:

- Existing properties of the structural members
- Properties of FRP syatem as specified by the supplier
- Design requirements and the trageted strengthening demands
- Quality control scheme and its implementaions
- Work conditions on the site and the project’s schedule
- The overall cost of the proposed strengthening system
- The gurantee that the proposed strengthening system can be effeciently implemented. The availability of the materials, certified applicators, and quality control means will form the bases upon which efficient implemintations of the strengthening system can be carried out.

This part presents guidence for the proper choice of FRP materials and systems. The designer must recognized the fact that FRP is an emergy technology. Consequently, the properties of FRP materials given in chapter 2 and the FRP systems presented in this chapter may rapidly improve or change with further research and development.

The use of untested or materials of unknown scourse shall be totally prohibited. Only systems and materials that have been tested and applied in reinforced concrete structures shall be used in FRP strengthening.

4.2.2 CHOICE OF STRENGTHENING AND REPAIR FRP MATERIALS

The choice of FRP materials for strengthening applications shall be made with reference to the physical, chemical and mechanical properties of the constituent materials of FRP systems given in Chapter 2, and after consideration of the compatibility of such materials with the environmental conditions, as listed in Table 4-1 in addition to those presented in Chapter 3.

TABLE 4-1: GUIDE FOR THE SELECTION OF FRP MATERIALS ACCORDING TO THE ENVIRONMENTAL EXPOSURE CONDITIONS

Condition	E-Glass	Aramid	Carbon
Passive load –Fabric added as ancillary structural support	✓		
Active load – Primary structure, stress less than 25% of the ultimate tensile strength	✓		
Active load – Primary structure, between 25 and 40% of the ultimate tensile strength			✓
Under water - Completely submerged or wet constantly			✓
Under water - Splash zone			✓
Strength driven applications	✓		✓
Stiffness driven applications			✓
Underground– cyclic moisture conditions; wet& dry	✓		✓
Extremely high impact situations		✓	
Electrical conductivity / galvanic cell concerns	✓		
Freshly poured concrete –internal or external application			✓
Extreme alkaline conditions; PH 9.5 –13.5			✓
Extreme acidic conditions; PH range 2.0 to 7.0	✓		
Low stress, high cycle fatigue	✓		
High stress, high cycle fatigue			✓
High compressive stresses			✓

4.2.3 CLASSIFICATION OF STRENGTHENING WORKS

Strengthening applications using externally bonded FRP composites can be categorized as either bond-critical or contact-critical applications. Bond critical applications depend on the existence of complete bond between the concrete substrate and FRP composites. Such applications include flexure, tension, shear and torsion strengthening. Contact-critical applications rely on the intimate contact between the FRP system and the concrete. Typical applications include column strengthening using FRP wrapping for confinement.

4.2.3.1 BOND-CRITICAL APPLICATION

The existing concrete substrate strength is an important parameter for bond-critical applications, including flexure or shear strengthening. It must possess the necessary strength to develop the design stresses of the FRP system through bond. Consequently, FRP systems shall not be used when the concrete substrate has a characteristic compressive strength, fcu, less than 20 MPa and tensile strength less than 1.5 MPa as determined by using a pull-off type adhesion test.

It may become necessary to remove thin layers of the concrete substrate and repeat the pull-off test in the case where test results failed to meet the preceding acceptable values. This process may be repeated, up until a sound concrete substrate surface is reached. In the case that the acceptable strength values given in this section are not met, the use of externally bonded FRP systems for such cases shall not be allowed. Alternatively, the use of anchoring systems to improve the proper connections of the externally bonded FRP system to the concrete substrate will be allowed subject to providing technical and experimental evidences of the soundness of such systems. Prior to FRP installation, the substrate surface shall be treated in accordance with provisions of section 4-4-1-3-2 and retested for compliance with the strength requirements specified in this section. The pull-off test shall meet the strength values given in this section.

4.2.3.2 CONTACT-CRITICAL APPLICATIONS

Contact-critical applications, such as column wrapping for confinement that rely only on intimate contact between the FRP system and the concrete are not governed by concrete substrate strength. Pull-off tests, will therefore, not be required for this type of application. Design stresses in the FRP system are developed by deformation or dilation of the concrete section in contact-critical applications. In applications involving confinement of structural concrete members, surface preparation shall promote continuous intimate contact between the concrete surface and the FRP system. Surfaces to be wrapped shall, at a minimum, be flat or convex to promote proper loading of the FRP system. Large voids in the surface shall be patched with a repair material compatible with the existing concrete. Materials with low compressive strength and elastic modulus, like plaster, can reduce the effectiveness of the FRP system and shall be removed.

4-2-4 FRP STRENGTHENING AND REPAIR SYSTEMS

A number of FRP systems are used for concrete strengthening and repair, as follows:

a- Externally Bonded Systems

- Systems that use FRP sheets, (section 4-2-4-1).
- Systems that use prefabricated FRP elements, (section 4-2-4-2).
- Special FRP systems, (section 4-2-4-3)

b- Near Surface Mounted Systems (N.S.M.)

In Near surface mounted systems, FRP bars and laminated strips are inserted inside slits cut into the concrete structure with a depth smaller than the concrete cover and bonded to the concrete into the slits.

4-2-4-1 FRP SHEETS AND LAMINATES

1- Dry unidirectional or multi-directional FRP sheets where fibers run predominantly in one direction, partially or fully covering the structural element. Installation on the concrete surface requires saturating resin usually after a primer has been applied. Two different processes can be used to apply the fabric:

A- Dry Lay-Up Systems: Dry FRP sheets can be applied directly into the resin which has been applied uniformly onto the concrete surface. Additional resin shall be applied onto the surface of FRP sheets in order to guarantee full saturation of the fibers with the resin.

B- Wet- Lay-up Systems: Dry FRP sheets can be impregnated with the resin either manually or, in a saturating machine and then applied wet to the concrete substrate.

2- **Pre-impregnate Systems:** Prepreg FRP systems consist of uncured unidirectional or multidirectional fiber sheets or fabrics that are pre-impregnated with a saturating resin in the manufacturer's facility. Prepreg systems are bonded to the concrete surface with or without an additional resin application, depending upon specific system requirements.

3- **Pre-cured FRP laminated strips:** FRP Laminated composites manufactured off site and bonded to the concrete surface using adhesive along with the primer and putty.

4- **Pre-cured Pre-impregnate FRP laminated strips:** The strips are bonded to the concrete surface with or without an additional resin application, depending upon specific system requirements.

4.2.4.2 PREFABRICATED ELEMENTS

Prefabricated elements are manufactured in the form of thin pultruded laminated strips or grids that may be delivered in a rolled coil, as well as in the form of pultruded factory-made shells, jackets or angles. The prefabricated elements are installed through the use of adhesives.

4.2.4.3 SPECIAL FRP SYSTEMS

Several special FRP systems have been developed; a number of such techniques are briefly explained as follows:

1- Automated Wrapping

The technique involves continuous winding of wet fibers under a slight angle around columns or other structures, such as chimneys by means of a robot. Key advantage of the technique, apart from good quality control, is the rapid installation.

2- Prestressed FRP System

In some cases it may be advantageous to bond the external FRP reinforcement onto the concrete surface in a prestressed state. Prestressing FRP reinforcement prior to bonding provides advantages similar to those achieved using the traditional prestressing systems.

3- In-Situ Fast Curing Using Heating Device

Instead of curing of the two-component adhesive of the bond interface under environmental temperature, heating devices can be used. In this way it is possible to reduce curing time, to allow bonding in regions where temperatures are too low to allow cold curing, to apply the technique in winter time, and to work with prepreg FRP types.

Different systems for heating can be used, such as electrical heaters, infrared heating systems and heating blankets.

4-FRP Impregnation by Vacuum

Vacuum impregnation is, to some extent, comparable with wet lay-up. The concrete element to be strengthened according to this method is pre-treated in the same manner as for the other methods. The surface is cleaned carefully, primer is applied and after curing of the primer the fibers are placed in predetermined directions. It is important that sheets or fabrics have channels where the resin can flow; otherwise special spacing material must be used. A vacuum bag is placed on top of the fibers, the edges of the bag are sealed and a vacuum pressure is applied. Two holes are made in the vacuum bag, one for the outlet where the vacuum pressure is applied and one for the inlet where the resin is injected.

4.2.5 CHOICE OF FRP STRENGTHENING SYSTEMS

The choice of **FRP** strengthening systems given in section 4-2-4 shall be made in accordance with the requirements of general considerations of section 4.2.1. Table 4-2 gives guidance for the selection of FRP systems according to the scopes of applications.

TABLE 4-2: GUIDE FOR THE SELECTION OF FRP SYSTEMS ACCORDING TO SCOPES OF APPLICATION

ELEMENTS AND SCOPES OF APPLICATION	EXTERNALLY BONDED FRP REINFORCEMENT			
	SHEETS			PREFABRICATED FRP LAMINATES
	CARBON	GLASS	ARAMID	
BEAMS:				
Flexural	B	B		A
Shear	A	B		B
Serviceability	B	C		A
SLABS:				
Flexural	B	B		A
Shear	A	B		C
Serviceability	B	C		A
COLUMNS:				
Flexural	A	B		B
Compression	A	B		B
Shear	A	B		B
Impact	B	A	A	C
Seismic	B	A		C
Serviceability	A	B		B
WALLS:				
Flexural	B	B		A
Shear	A	B		C
Impact	B	A	A	C`
Seismic	B	A		B
Blast	A	B	A	B
Serviceability	B	B		A
A= Most Recommended		B=Recommended		C= Not Recommended

PART 3
4.3 LIMIT STATES DESIGN METHOD

4.3.1 GENERAL DESIGN CONSIDERATIONS

a- This section presents the main principles for the design of FRP systems for externally strengthening concrete structures according to the limit states design method. Such limit states insure sufficient safety against failure as the cross-section reaches its ultimate strength limit as will be presented in Section 4-3-2,as well as, fulfilling all the serviceability requirements according to Section 4-3-3. The main design principles take into consideration the mechanical properties of FRP given in Chapter 2 and the durability considerations presented in Chapter 3 of this Code. The reinforced concrete design principles stated in the Egyptian Code for the Design and Construction of Concrete Structures, ECP203 must be fulfilled, in addition to the requirements of this code.

b- The design principles given in this section are limited only to the use of externally bonded FRP systems for strengthening concrete elements.

c- The use of FRP is limited to the cases in which the fibers are subjected to tensile stresses only. FRP shall not be used to resist compressive stresses. They can be used, however, in cases where they are subjected to reversal loadings causing tension and compression stresses. For such cases the contribution of FRP in resisting compressive stresses shall be ignored.

d- FRP systems are effective in strengthening and repair of structural members subjected to flexure, (Section 4-3-2-1) and tension, (Section 4-3-2-3) through bonding FRP reinforcement with fibers oriented along the length of member. They are also effective for shear strengthening (Section 4-3-2-2) and for increasing the ultimate strength and the ductility of members subjected to compression forces through providing additional confinement to the cross-section (Section 4-3-2-3). The traditional FRP systems are not effective in enhancing punching shear and bearing strengths. For such cases, special FRP systems could be employed provided that sufficient evidence of their efficiencies could be provided through well established studies and tests.

e- FRP systems are very efficient for seismic strengthening and retrofitting of structures. They can be used in cases that require enhancing the ductility of columns and the shear strength of concrete elements confining the cross-section of the column and concrete members using FRP with fibers oriented in a direction perpendicular to the axis of the column (Section 4-3-2-3). In case of flexural strengthening of the beams of ductile moment resisting frames (Section 4-3-2-1), one shall make sure that brittle shear failure shall not take place. Also, all the requirements of the Egyptian Code for the Design and Construction of Concrete Structures, (ECP 203) shall be fulfilled.

4.3.1.1 DESIGN PHILOSOPHY

The design of the strengthening works shall be carried out using the Limit states design method which is based on satisfying the following requirements:

1- **Ultimate strength limits state**: This limit state provides guarantees for the satisfaction of all safety requirements and for assessing the mode of failure of the structure after strengthening. Safety requirements are satisfied by using the ultimate loads defined in the Egyptian Code for the Design and Construction of Concrete Structures, ECP-203. Material strength reduction factors for concrete and reinforcing steel for the cases involving the increase of shear strength and for members subjected to tensile or compressive forces shall be conform to the values given in the ECP203. For members subjected to flexure, material strength reduction factors for concrete and reinforcing steel, as well as, for FRP, shall conform to the values given in Section 4-3-2-1-7 of this code, such values depend on type of application, nature of use, mode of failure and the importance of the member. These values shall be considered as the minimum acceptable values. They can be increased according to special strengthening requirements.

2- **Serviceability limits states**. Such limit states include provisions for the control of deflection, vibration and cracking of structural elements. They must satisfy all corresponding requirements of ECP-203.

3- **The characteristics and ultimate strengths of the FRP:** they shall be taken in accordance with the properties given in Chapter 2 with due consideration to the durability requirements of Section 3-14-3 of Chapter 3 of this code.

4.3.1.2 STRENGTHENING LIMITS

When designing strengthening systems, consideration shall be given to determining strengthening limits. These limits are imposed to safeguard the structure against collapse in the cases where the efficiency of the FRP strengthening system is lost due to fire, vandalism or any other causes that could adversely affect the efficiency of the strengthening system.

In some cases, the values of the strengthening limits are imposed in order to guarantee that the strengthened member satisfy the serviceability requirements of the ECP-203 as well as the requirements of Section 4-3-1-2-1 of this code.

4.3.1.2.1 Effective Strengthening Limits

The values of effective strengthening shall be limited to those values that shall guarantee for all members of the structure and parts thereof full satisfaction of the strength and serviceability requirements of the ECP 203 Also, their values shall be less than the limits specified for fire endurance of the structure given in Section 4-3-1-2-2.

4.3.1.2.2 Strengthening Limits for Structural Fire Endurance

The design philosophy for the safety of FRP strengthened structure when exposed to fire for the duration of the fire resistance rating of the structure without providing efficient means for fire protection, is based on the principle that the efficiency of all FRP strengthening works shall be totally lost along with the reduction of the strength of the structure, but without causing the structure to collapse, as follows:

1- The efficiency of all FRP strengthening works shall be totally lost in the case that the temperature of the epoxy resin of the FRP system exceeds the glass transition temperature of the resin which for the commercially available resins varies between 60to 80 C^o, resulting in un-strengthened structures not satisfying the safety provision of the Egyptian concrete code, (ECP203) for the duration of fire resistance rating required by the Egyptian fire code.

2- In the cases of not using special heat resistant resins along with providing efficient fire protection system capable of controlling the temperature of the resin to values below the resin's Tg temperature, the safety of the un-strengthened structure that resulted from fire exposures shall be maintained by satisfying the following Equation. (4-1) with due consideration of the reduction in the yield strength of steel and the compressive strength of concrete:

$$U = 1.2\,DL + 0.85\,LL \qquad (4\text{-}1)$$

Where,

DL = Dead loads

LL = Live loads

2- In the cases of using special heat resistant resins along with providing fire protection system capable of protecting the elements of the structure, the safety of the un-strengthened structure that resulted from fire exposures shall be maintained by satisfying the following Equation. (4-2)

$$U = DL + LL \qquad (4\text{-}2)$$

3- It is noted that Equations 4-1 & 4-2 will not govern the design of FRP strengthened members in the cases of using special heat resistant resins along with providing efficient fire protection system capable of controlling the temperature of the resin to values below the resin's Tg temperature. For such cases, the design shall be governed by the ultimate load combination of the ECP203. However, such fire protection systems shall be used only after carrying out extensive verification testing to prove their efficiencies. In addition, all fire protected members shall be capable of providing fire endurance rating for the FRP system having duration equals at least 1.5 the designed fire endurance rating of the structure specified by the Egyptian fire code.

4.3.2 Strength Limit State

4.3.2.1 Flexural Strengthening

4.3.2.1.1 General Considerations

a- This section presents guidance for the design of the flexural strengthening of reinforced concrete members. It presents the concepts and equations used in the design of flexural strengthening of concrete members using FRP composites externally bonded to the tension face of rectangular cross-sections. The general concepts outlined herein can also be extended to nonrectangular shapes and to members with compression steel reinforcement. In the case of prestressed concrete members, strain compatibility with respect to the state of strain in the stressed member shall be used for the evaluation of the FRP contribution. Additional failure modes controlled by rupture of prestressing tendons shall also be considered .

b- When FRP reinforcement is used to increase the flexural strength of a member, it is important to verify that :

- The member is capable of resisting the additional shearing forces associated with the increase of the flexural strength in order to avoid sudden brittle shear failure. If additional shear strength is required, FRP laminates shall be used to resist the additional shear forces as given in Section 4-3-2-2.
- In the case of flat slab structures, the slab shall be capable of resisting the additional punching shearing forces associated with the

increase of the flexural strength of the slab as a result of using FRP strengthening.

- The use of FRP reinforcement to increase the flexural strength of beams and slabs shall not lead to increasing the values of the deflection beyond the limits given in the Egyptian Code for the design and Construction of Concrete Structures, (ECP 203).

c- The increase of the flexural strength of concrete members strengthened with FRP shall be kept within the limits given is Section 4-3-1-2 and Section 4-3-2-1-2.

d- The use of externally bonded FRP reinforcement for flexural strengthening will reduce the ductility of the original member. Such a reduction in ductility could lead to changing the ductile flexural failure mode to a brittle failure mode. In such cases, the material strength reduction factors of concrete and reinforcing steel given in the Egyptian Code for the design and Construction of Concrete Structures, (ECP 203) shall be modified to conform to Section 4-3-2-1-7. It is also important to use values for the material strength reduction factors for FRP that reflect the mode of failure of the element (Section 4-3-2-1-7).

e- FRP systems given in this section shall not be used for the cases of ductile moment resisting frames contributing to resisting seismic loads.

4.3.2.1.2 Limits of Flexural Strengthening

a- The values of the limits of flexural strengthening are affected by several interactive factors depending on the nature of the member. The limits of flexural strengthening shall, therefore, be governed by the adverse affects on the other types of strengths (i.e. shear strength, punching strength) and serviceability of the member, as well as on all other members adversely affected by the flexural strengthening.

b- The possibility of changing the mode of failure of the member from a ductile mode to a brittle failure mode as a result of FRP strengthening shall result in a structure not satisfying the seismic requirements of the Egyptian Code for the design and Construction of Concrete Structures, (ECP 203).

c- The increase of the flexural strength of a member due to the use of FRP reinforcement is limited by the requirements of fire resistance rating of the structure (Section 4-3-1-2-2) or 1.4 times the original flexural strength whichever is greater.

4.3.2.1.3 Basic Assumptions

The strength limit state of the cross-sections subjected to flexure and strengthened using externally bonded FRP shall satisfy the compatibility and the equilibrium conditions, in addition to the following assumptions and general considerations:

1- Design calculations shall be based on the actual dimensions, internal reinforcing steel arrangement, and material properties of the existing member being strengthened.
2- Strains are linearly distributed over the cross-section and consequently, the strains in the reinforcement, concrete and FRP are directly proportional to the distance from the neutral axis.
3- The maximum usable compressive strain in the concrete is 0.003.
4- The tensile strength of concrete is neglected and all the tensile stresses are resisted by the reinforcing steel and the FRP.
5- There is no relative slip between external FRP reinforcement and the concrete.
6- The FRP reinforcement has a linear elastic stress-strain relationship to failure (Fig. 4-1). The stress-strain relationship for concrete in compression and the stress-strain relationship for the reinforcing steel are those given in the Egyptian Code for the Design and Construction of Concrete Structures.

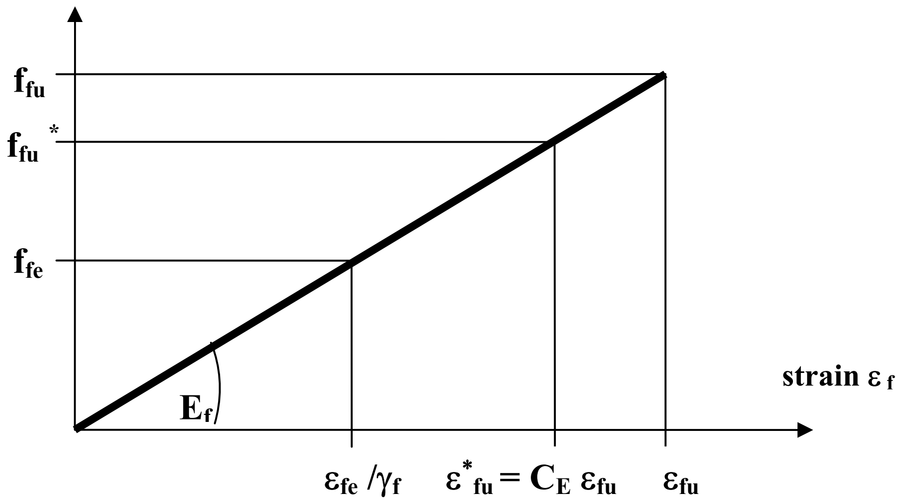


Fig. (4-1) Stress-strain curve for FRP

4.3.2.1.4 Ultimate Flexural Moment of the Cross-Sections

a- The ultimate flexural strength of the cross-sections strengthened using externally bonded FRP shall be calculated based on satisfying the compatibility and the equilibrium conditions. The material strength reduction factors given in Section 4-3-2-1-7 shall be used in the design of the sections with due consideration of the nature of failure according to (4-3-2-1-5).

b- Unless all the loads are removed before installation of FRP reinforcement, the strain value in the reinforcing steel resulting from the service loads acting on the member during the installation shall be calculated using elastic analysis of cracked concrete cross-sections. These strains shall be considered as initial strains and shall be excluded from the strain in the FRP when calculating the ultimate flexural moment of the cross-section.

4.3.2.1.5 Failure Modes

a- The flexural strength of a section strengthened with FRP depends on the controlling failure mode. The following failure modes shall be investigated:

- Crushing of concrete in compression before yielding of the reinforcing steel.
- Yielding of the steel in tension followed by rupture of the FRP laminate.
- Yielding of the tension steel followed by concrete crushing.
- Shear/tension delamination of the concrete cover (cover delamination.
- Debonding of the FRP from the concrete substrate (FRP debonding).

b- Concrete crushing is assumed to occur if the maximum compressive strain in the concrete reaches 0.003. Rupture of the FRP laminate is assumed to occur if the strain in the FRP reaches its design rupture strain ($\varepsilon_f = \varepsilon^*_{fu}$) before the concrete reaches its maximum usable strain. Equation 3-5 of Chapter 3 gives the values of ε^*_{fu}.

c- Cover delamination or FRP debonding can occur if the force in the FRP cannot be sustained by the substrate. In order to prevent debonding of the FRP laminate, a limitation on the strain level developed in the FRP is placed. Such a limitation is given by Eq. (4-3) that gives an expression for the bond-dependent coefficient k_m, which shall be satisfied in addition to fulfilling the requirements of Sections 4-3-2-4-3 and 4-3-2-4-4 dealing with the detaining and anchorage of the FRP laminates.

$$\varepsilon_{fe} = k_m \ \varepsilon^*_{fu} \qquad (4\text{-}3a)$$

$$k_m = \begin{cases} \dfrac{1}{60\ \varepsilon^*_{fu}}\left(1 - \dfrac{n\ E_f\ t_f}{360000}\right) \le 0.09 & \text{for } n\,E_f\,t_f \le 180000 \\ \dfrac{1}{60\ \varepsilon^*_{fu}}\left(\dfrac{90000}{n\,E_f\ t_f}\right) \le 0.09 & \text{for } n\,E_f\,t_f \rangle\ 180000 \end{cases} \qquad (4\text{-}3b)$$

in which
n = number of plies of FRP reinforcement where the strength is computed
E_f = tensile modulus of elasticity of FRP
t_f = thickness of one ply of the FRP reinforcement

The value of the coefficient k_m shall not be more than 0.9 in order to prevent cover delamination of FRP debonding at the end of the external reinforcement. It should be noted that as the stiffness of the FRP laminates increases the value of the coefficient k_m decreases.

4.3.2.1.6 Ductility

The use of externally bonded FRP reinforcement for flexural strengthening reduces the ductility of the member. Such a loss in ductility could change the mode of failure of the strengthened member from a ductile to brittle modes of failure and the ductility of strengthened members shall be calculated accordingly. To achieve adequate ductility, the strain the steel at the point of concrete crushing or failure of the FRP, including delamination or debonding, shall at least be equal to:

$\varepsilon_s = 0.005$ for steel grade 240/350

$\varepsilon_s = 0.0065$ for steel grade 400/600 (4-4)

4.3.2.1.7 Material Strength Reduction Factors

Material Strength reduction factors for concrete, reinforcing steel, and FRP are taken according to the relationships given in (4-5) and figure (4-2).

Ductile Failure — For $\varepsilon_s \geq 0.005$ (Steel 240/350)

For $\varepsilon_s \geq 0.0065$ (Steel 400/600)

$\gamma_c = 1.5 \qquad \gamma_s = 1.15$

For FRP sheets $\gamma_f = 1.5$

For FRP laminates $\gamma_f = 1.4$ (4-5-a)

Brittle Failure — For $\varepsilon_s \geq 0.005$ (Steel 240/350) &

For $\varepsilon_s \geq 0.0065$ (Steel 400/600)

$\gamma_c = 1.5\eta \qquad \gamma_s = 1.15\eta$

For FRP sheets $\gamma_f = 1.5\eta$

For FRP laminates $\gamma_f = 1.4\eta$

Where:

$$\eta = 1 + 0.15\left[0.005 - \varepsilon_s\right] / \left\lfloor 0.005 - \varepsilon_{sy} \right\rfloor \qquad \text{(Steel 240/350)}$$

$$\eta = 1 + 0.15\left[0.0065 - \varepsilon_s\right] / \left\lfloor 0.0065 - \varepsilon_{sy} \right\rfloor \qquad \text{(Steel 400/600)} \qquad (4\text{-}5\text{-}b)$$

For $\varepsilon_s \langle \ \varepsilon_{sy}$

$\gamma_c = 1.7 \qquad \gamma_s = 1.32$

For FRP sheets $\gamma_f = 1.7$

For FRP laminates $\gamma_f = 1.6$ (4-5-c)

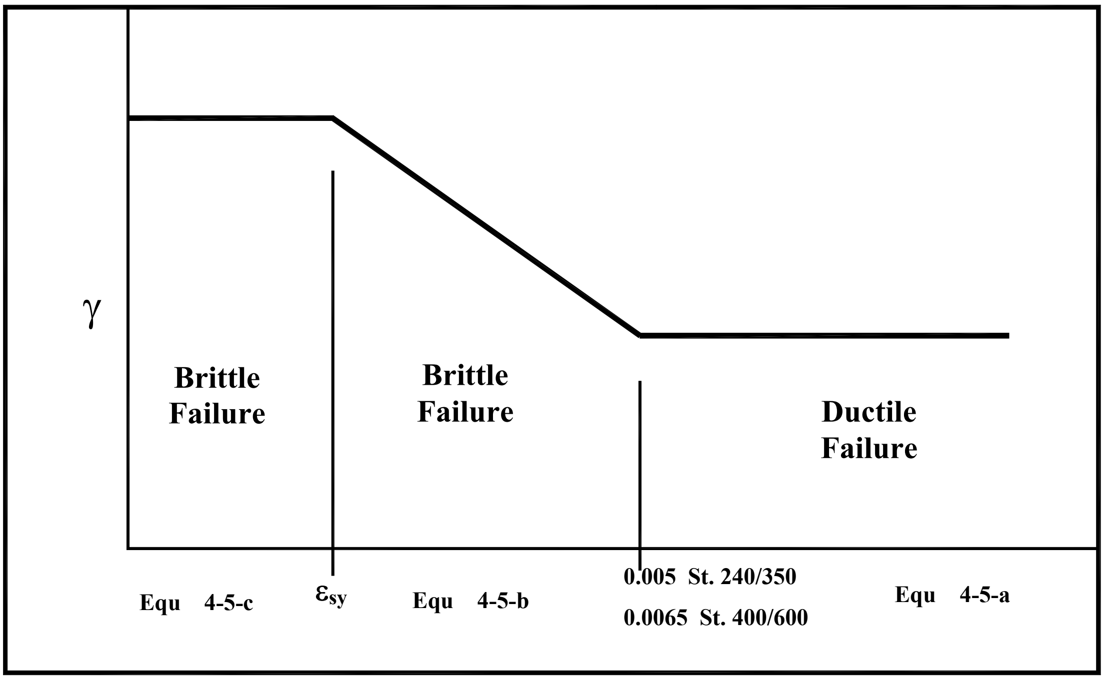


Fig. (4-2) Material Strength reduction factors for concrete, steel and FRP laminates

4.3.2.1.8 Strain Level in the FRP Reinforcement

It is important to determine the strain level in the FRP reinforcement at the ultimate moment of the cross-section (Section 4-3-2-1-4-b). The value of the strain permitted in the FRP laminates at section failure (ε_{fe}) shall be governed by either the strain level developed in the FRP at the point at which concrete crushes, the point at which the FRP ruptures, or the point at which the FRP debonds from the substrate. The value of this strain can be calculated from Eq. (4-6).

$$\varepsilon_{fe} = \varepsilon_{cu} \left(\frac{h - c}{c} \right) - \varepsilon_{bi} \leq k_m \, \varepsilon^{*}_{fu} \qquad (4\text{-}6)$$

Where:

ε^{*}_{fu}= Design rupture strain in the FRP with due consideration of the environmental effects and its value is given by Eq. (5-3) of Chapter 3.

ε_{bi}= Initial strain in concrete at the level of the FRP at service load level when installing the FRP (Section 4-3-2-1-4-b)

4.3.2.1.9 Maximum Design Stress in the FRP

The value of the permissible strain in the FRP given by Eq. (4-6) and the stress-strain relationship of the FRP (Fig. 4-1) determine the maximum stress that can be developed in the FRP reinforcement before flexural failure of the section through the following relation:

$$f_{fe} = E_f \ \varepsilon_{fe} / \gamma_f \qquad (4\text{-}7)$$

4.3.2.1.10 Serviceability Requirements

The serviceability requirements shall be satisfied according to Section 4-3-3.

4.3.2.1.11 Application to Rectangular Sections under Flexure and Reinforced in Tension

The calculation procedure used to arrive at the ultimate flexural strength of the cross-sections strengthened using externally bonded FRP should satisfy the compatibility and the equilibrium conditions and shall consider the governing mode of failure. Such a procedure needs a trail and error method to insure the satisfaction of the requirements of compatibility and equilibrium. Figure 4-3 shows the strains and stresses distribution in a section subject to an ultimate moment.

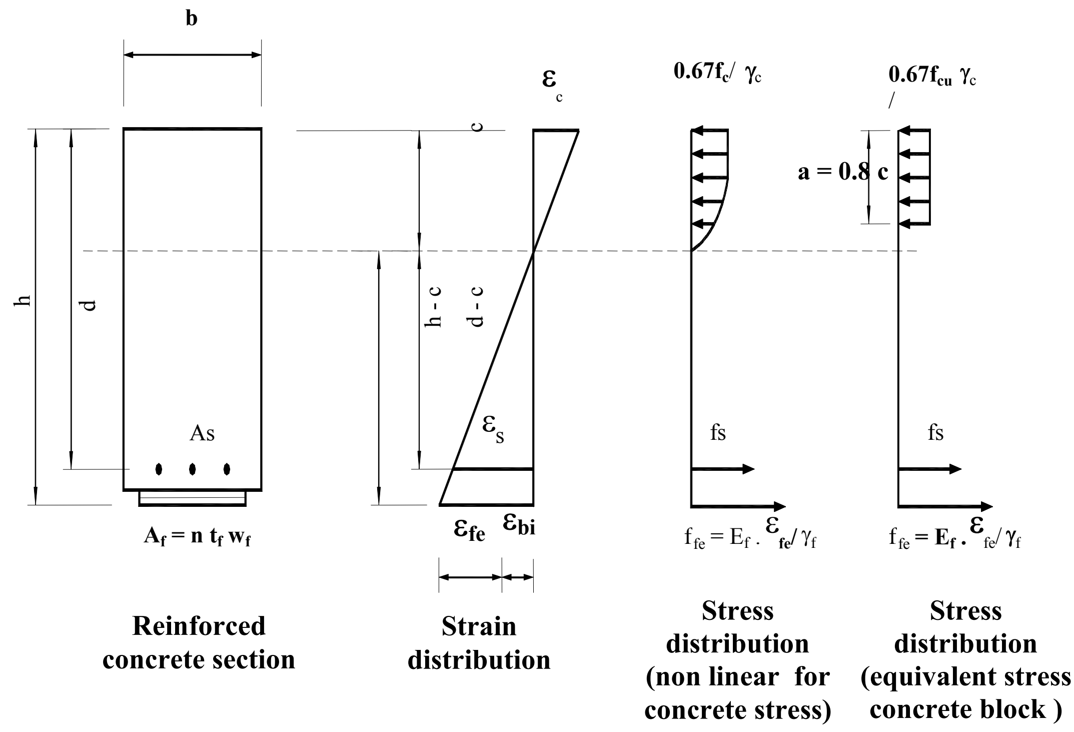


Fig. (4-3) Stress and Strain distributions in a rectangular section subject to an ultimate flexural moment

The values of the strains and stresses developed in the reinforcing steel are calculated from Eqs. 4-8 and 4-9, respectively, using a trail and error method.

$$\varepsilon_s = (\varepsilon_{fe} + \varepsilon_{bi})\left(\frac{d-c}{h-c}\right) \quad (4\text{-}8)$$

$$f_s = E_s\,\varepsilon_s \le f_y/\gamma_s \quad (4\text{-}9)$$

The depth of the equivalent rectangular stress block of the compressed concrete is calculated from Eq. (4-10)

$$a = \frac{A_s\,f_s + A_f\,f_{fe}}{(0.67\,f_{cu}\,b)/\gamma_c} \quad (4\text{-}10)$$

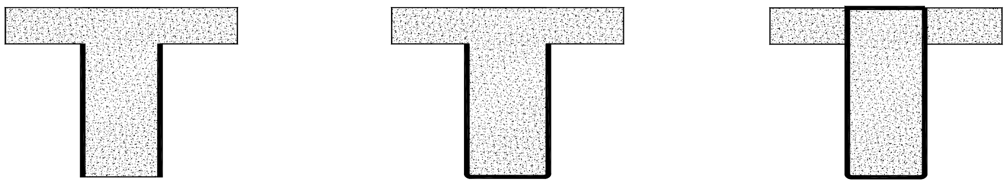
The ultimate flexural moment is calculated from Eq. (4-11)

$$M_u = A_s\,f_s\left(d - \frac{a}{2}\right) + A_f\,f_{fe}\left(h - \frac{a}{2}\right) \quad (4\text{-}11)$$

4-3-2-2 SHEAR STRENGTHENINH

4.3.2.2.1 General Considerations

a- FRP systems can be used in shear strengthening of reinforced concrete beams and columns. There are three types of FRP wrapping systems that can be used to increase the shear strength of reinforced concrete beams and columns. In the first system, the FRP composites are completely wrapped around the section on all four sides (Fig. 4-4-a). This wrapping system is the most efficient one and is commonly used in strengthening columns and in some cases it can be used in strengthening beams. Partial wrapping is usually used in beam applications, where a monolithic slab makes it impractical to completely wrap the beam. In the second method, the FRP composite is partially wrapped around three sides of the member (U-shaped) (Fig. 4-4-b), whereas FRP composites are bonded to the two sides of the member in the third technique, which is the least efficient (Fig. 4-4-c)



2 sides Wrapping
Fig. (4-4-c)

3 side Wrapping
Fig. (4-4-b)

Full Wrapping
Fig(4-4-a)

Fig. (4-4) Methods of strengthening concrete member for shear resistance

b- The FRP system can be installed continuously along the span length of a beam or placed as discrete strips (Fig. 4-5)

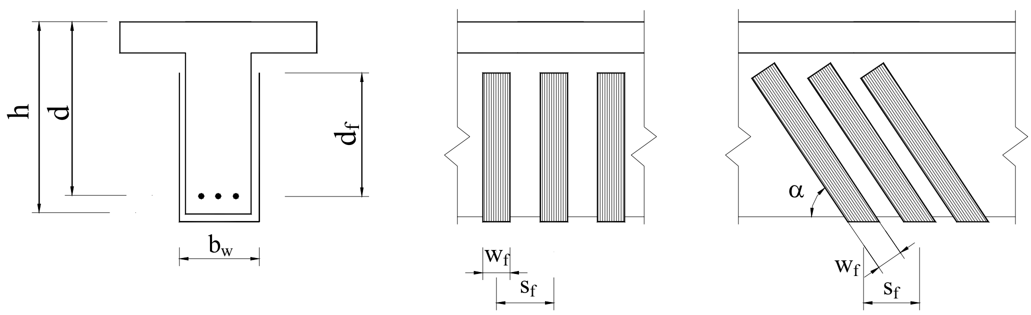


Fig. (4-5) Definition of variables required for calculating shear strength of FRP Composites

c- Consideration shall be given to leaving distances between FRP laminates (Section 4-3-2-4-8) when using continuous FRP reinforcement that completely encases the member and may prevent the migration of moisture.

d- The value of the material strength reduction factor of the FRP, γ_f depends of the FRP wrapping shear strengthening system. Unless otherwise mentioned, the value of γ_f is taken as follows:

$\gamma_f = 1.5$ Complete wrapping scheme (Fig. 4-4-a) (4-12a)

$\gamma_f = 1.6$ Partial wrapping scheme (Fig. 4-4-b or –c) (4-12b)

4.3.2.2.2 Nominal Shear Strength of Concrete Members Strengthened with FRP Composites

The nominal shear strength of an FRP-strengthened concrete member shall be determined by adding the nominal shear strength of the FRP to the nominal shear strengths of the concrete and the reinforcing steel as given in the ECP203 as follows:

$$q_u = 0.5\, q_{cu} + q_{su} + q_{fu} \qquad (4\text{-}13)$$

Where,

q_u = Nominal shear strength

q_{su} = Nominal shear strength of reinforcing steel

q_{cu} = Nominal shear strength of concrete

q_{fu} = Nominal shear strength of FRP

In all cases, the nominal shear strength of FRP strengthened members shall not be more than the following:

$$q_{umax} = 0.7\sqrt{\frac{f_{cu}}{\gamma_c}} < 3.0 \text{ N/mm}^2 \qquad (4\text{-}13b)$$

4.3.2.2.3 Nominal Shear Strength of FRP

The nominal shear strength of the FRP shear reinforcement shall be given to the Equation 4-14, as follows :

$$q_{fu} = A_f \left(E_f\, \varepsilon_{ef} / \gamma_f\right)\left(\sin\alpha + \cos\alpha\right)\left(d_f / d\right) / \left(S_f \,.\, b_w\right) \qquad (4\text{-}14a)$$

$$A_f = 2\, n\, t_f\, w_f \qquad (4\text{-}14b)$$

Where,

A_f = area of FRP external reinforcement (equation 4-14b)

E_f = tensile modulus of elasticity

ε_{ef} = effective strain in FRP reinforcement (equation 4-15 for complete wrapping and equation 4-18 for partial wrapping)

γ_f = Material strength reduction factor of FRP shear reinforcement (Section 4-3-2- 2-1-d)

α = angle of inclination of FRP reinforcement to the longitudinal axis of the member

d = effective depth of the concrete section

d_f = depth of FRP shear reinforcement
S_f = spacing of FRP shear reinforcement (distance between the centerline of the strips)
b_w = width of concrete section
n = number of plies of FRP reinforcement
t_f = nominal thickness of one ply of the FRP reinforcement
w_f = with of the FRP reinforcing plies

The spacing S_f shall be less than d/4 or 200 mm whichever is smaller, in addition to the width of the FRP composites measured in the direction of the member axis, as shown in Figure 4-5.

4.3.2.2.4 Effective Strain in FRP Laminates

The effective strain is the maximum strain that can be achieved in the FRP system at the ultimate loads. Its value shall be governed by the failure modes of the FRP system and that of the strengthened reinforced concrete member according to the following:

4.3.2.2.4.a Complete Wrapping System

For reinforced concrete members completely wrapped with FRP composites (Fig. 4-4-a), the value of the effective fiber strain shall be limited to 0.4%, as given by Equation 4-15. Such a limitation shall be imposed to insure preserving the aggregate interlock (internal friction) necessary for the concrete contribution to the shear strength of the member, as follows:

$$\varepsilon_{ef} = 0.75\ \varepsilon^{*}_{fu} \leq 0.004 \qquad (4\text{-}15)$$

Where,
ε_{ef} = effective strain if the FRP
ε^{*}_{fu} = maximum strain in the FRP according to Equation 3-5 of Chapter 3.

4.3.2.2.4.b Partial Wrapping Scheme

1- In FRP systems that do not enclose the entire section (two- and three-sided wraps) as shown in Figures. 4-4-b and c, failure shall result from debonding of the FRP composites from the concrete (Section 4-3-2-4-3) due to the increase of the bond stresses. Such a behavior shall occur at a strain level less than the maximum allowable strain given in Equation 4-15. In such a case, the value of the effective strain in the FRP shall be reduced in order to guarantee the efficiency of the active bond length needed to preserve the bond between the FRP and concrete when reaching the ultimate load resulting from debonding of the FRP from concrete. It is noted that rounding of the beam edges shown in Fig. 4-4-a and b is essential

2- The active bond length, L_e and the bond strength reduction factor k_v shall be calculated using Equations (4-16-a) and (4-16-b). Their values depend on the characteristic strength of concrete (f_{cu}) and the stiffness of the FRP laminate ($n\ t_f\ E_f$) with the value of the effective strain calculated using Equation 4-18, as follows :

$$L_e = 23300/(n\,t_f\,E_f)^{0.58} \qquad (4\text{-}16a)$$

$$k_v = k_1\,k_2\,L_e/(11900\ \varepsilon^*_{fu}) \leq 0.75 \qquad (4\text{-}16b)$$

Where,

k_1 is a factor that depends on the concrete strength and is calculated from the following relation:

$$k_1 = (f_{cu}/33.75)^{2/3} \qquad (4\text{-}17a)$$

k_2 is a factor that depends on the partial wrapping system used and shall be calculated from the following relations:

$$k_2 = (d_f - L_e)/d_f \qquad \text{(three-sided wrap)} \qquad (4\text{-}17b)$$

$$k_2 = (d_f - 2L_e)/d_f \qquad \text{(two-sided wrap)} \qquad (4\text{-}17c)$$

3- In case of partial wrapping, the effective strain shall be calculated using the following equation:

$$\varepsilon_{ef} = k_v\ \varepsilon^*_{fu} \leq 0.004 \qquad (4\text{-}18)$$

4- In order to increase the anchorage effectiveness, special anchorage systems, similar to those shown in section 4-3-2-4-9, can be used.

4-3-2-3 AXIAL COMPRESSION, AXIAL TENSION, AND DUCTILITY ENHANCEMENT

4.3.2.3.1 Axial Compression

4.3.2.3.1.1 General

a- FRP jackets can be used to increase the axial compression strength of a concrete member by providing confinement with an FRP jacket

b- Confining a concrete member is accomplished by orienting the fibers transverse to the longitudinal axis of the member. It is noted that any contribution of fibers longitudinally aligned with the column axis to compression strength of the column shall be neglected.

c- For columns with circular cross-sections, both complete wrapping of the entire column height and partial wrapping at selective locations can be used.

d- For columns with rectangular cross-sections, only complete wrapping of entire height of the column shall be allowed.

e- FRP wrapping provides passive confinement to the compression member. As such, FRP jackets shall remain unstressed until dilation and cracking of the wrapped compression member occur.

f- Intimate contact between the FRP jacket and column section is critical and shall be assured by satisfying the serviceability requirements of Section 4-3-3-2.

g- The lateral confinement of rectangular columns having rectangularity ratio of the column section (t/b) greater than (1.5) , as well as for sections having one of the sections dimensions greater than 650 mm shall be considered as ineffective. However, for such rectangular columns, the use of special types FRP jackets for increasing the axial compressive strength of columns can be allowed if it can be proven that the analyses of such systems are based on sound engineering principles that satisfy the conditions of equilibrium and strain compatibility. Such analyses shall be confirmed with the results of sufficient number of tests.

h- The effect of increasing the axial compressive strength of the column on its resistance to buckling shall be addressed according to the requirements of the Egyptian Code for the Design and Construction of Concrete structures (ECP 203).

i- The increase of the axial compressive strength of the column as a result of using external FRP jacket shall be limited by the fire requirements given in section 4-3-1-2-1.

j- For all the cases covered in this section, the material strength reduction factor of the FRP γ_f shall be taken equal to 1.3.

k- The effective strain in the FRP jackets, ε_{ef} shall be evaluated using the following relation :

$$\varepsilon_{fe} = 0.75\ \varepsilon^{*}_{fu} \leq 0.004 \qquad (4\text{-}19)$$

where ε^{*}_{fu} is the maximum strain in the FRP as given Equation. 3-5 of Chapter 3.

l- Lap splices of FRP shall be made in accordance with Section 4-3-2-4-7

4.3.2.3.1.2 Ultimate Compressive Strength of Sections Strengthened with FRP Wraps and Subject to Axial Compression

The ultimate compressive strength of concrete sections subject to axial compression and strengthened with FRP jacket shall be calculated using the following equations:

1- For columns with transverse steel tie reinforcement:

$$P_u = 0.35 f_{cuc} A_c + 0.67 f_y A_{sc} \qquad (4\text{-}20\text{-}a)$$

2- For columns with spiral reinforcement satisfying the requirements of the Egyptian Code for the Design and Construction of Concrete structures:

$$P_u = 0.40 f_{cuc} A_c + 0.76 f_y A_{sc} \qquad (4\text{-}20\text{-}b)$$

Where,

A_c = the net area of the concrete

A_{sc} = area of longitudinal reinforcing steel

f_y = yield strength of longitudinal steel reinforcement

f_{cuc} = the confined compressive strength of concrete as a result of the use of FRP jacket. It shall be calculated using the following equation:

$$f_{cuc} = f_{cu}\left[2.25\sqrt{1+9.875\frac{f_l}{f_{cu}}} - 2.5\frac{f_l}{f_{cu}} - 1.25\right] \qquad (4\text{-}21)$$

Where,

f_{cu} = characteristic compressive strength of concrete

f_l = confining pressure due to FRP jacket

f_l shall be calculated for circular columns in accordance with section 4-3-2-3-1-3 and for non-circular columns including rectangular columns in accordance 4-3-2-3-1-4.

4.3.2.3.1.3 Circular Columns

4.3.2.3.1.3.a Confining pressure–Case of fully Wrapped Circular Columns

For the case of fully wrapped circular columns, the confining pressure f_l shall be calculated using the following equation:

$$f_l = \frac{\rho_f E_f \varepsilon_{fe}}{2\gamma_f} \qquad (4\text{-}22)$$

Where,

E_f = tensile modulus of elasticity of the FRP

μ_f = volumetric ratio of FRP reinforcement in case of full wrapping and shall be taken equals to:

$$\mu_f = \frac{4\,n\,t_f}{D} \qquad (4\text{-}23)$$

Where,

n = number of plies of FRP reinforcement

t_f = nominal thickness of one ply of FRP

D = diameter of column

4.3.2.3.1.3.b Confining pressure–Case of Partially Wrapped Circular Columns

For the case of partially wrapped circular columns, the confining pressure f_l shall be calculated from the following equation:

$$f_l = K_e \frac{\mu_f E_f \varepsilon_{fe}}{2\gamma_f} \qquad (4\text{-}24)$$

Where,

μ_f = volumetric ratio of FRP reinforcement in case of partial wrapping and shall be taken equals to:

$$\mu_f = \frac{4\ b_f\ n\ t_f}{S D} \qquad (4\text{-}25)$$

K_e is a confinement effectiveness coefficient given by:

$$K_e = \left(1 - \frac{(S - b_f)}{2D}\right)^2 \ \langle\ 1 \qquad (4\text{-}26)$$

Where,

b_f = width of the FRP reinforcing plies

S= vertical distance between two successive FRP reinforcing plies, (Fig. 4-6).

the values of n, D & t_f - as defined in section 4-3-2-3-1-3-a..

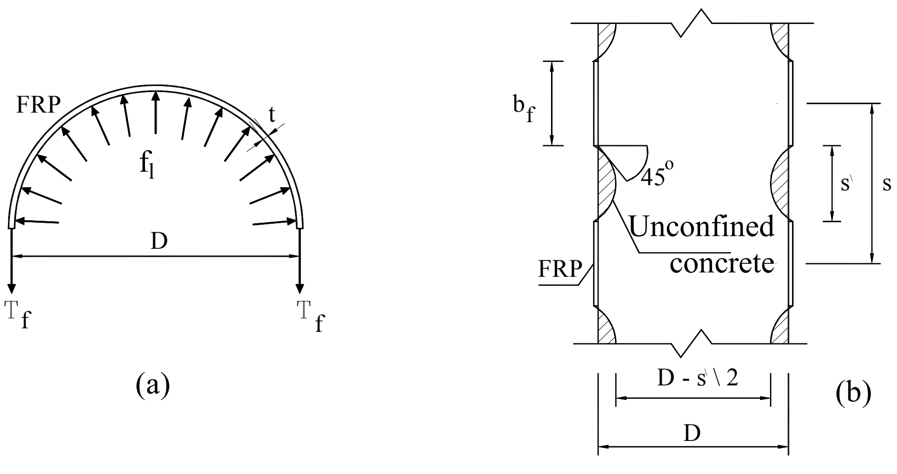


Fig. (4-6) Partial wrapping of circular column

4.3.2.3.1.4 Rectangular and Non-circular Columns – Case of Full Wrapping

4.3.2.1.4.a Efficiency of Strengthening of Non-circular Columns

Testing has shown that confining square or rectangular or non-circular columns with FRP jackets can provide marginal increase in the axial compression strength of the member. Applications of this nature shall be closely evaluated. This section gives the requirements and limitations for the use of FRP wraps for strengthening non-circular sections. Generally, the efficiency of the FRP wraps can be increased when strengthening non-circular sections if the edges of the sections are rounded with a radius r_c as shown in Fig. 4-6. As the use of FRP systems undergoes continuous development, it is permitted to use FRP systems other than those mentioned in this section. Such permission is subject to providing proof of the efficiency of the system through carrying out a sufficient number of tests. Such test results shall proved evidence for the satisfaction of the conditions of equilibrium and strain compatibility.

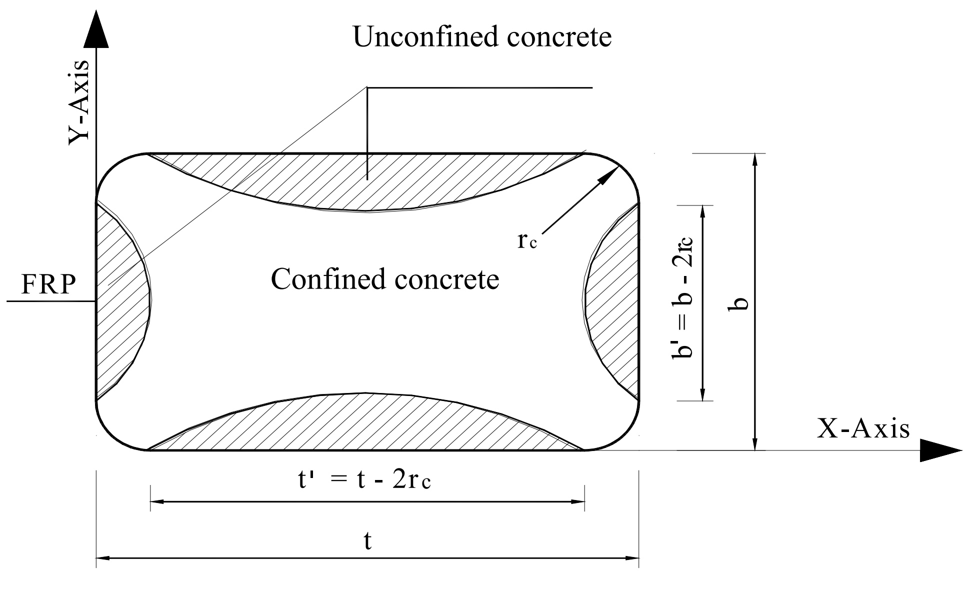


Fig. (4-7) Efficiency of confinement of a rectangular section

4.3.2.3.1.4.b Confining Pressure in Non-circular Sections

The confining pressure f_l shall be calculated using equation (4-27):

$$f_l = K_e \frac{\mu_f E_f \varepsilon_{fe}}{2\gamma_f} \qquad (4\text{-}24)$$

The volumetric ratio of FRP reinforcement for rectangular columns shall be calculated using the following equation:

$$\mu_f = \frac{2\ n\ t_f\ (b+t)}{b\,t} \qquad (4\text{-}25)$$

The confinement effectiveness coefficient for the case of full wrapping of a rectangular column is given as:

$$K_e = 1 - \frac{(b - 2r_c)^2 + (t - 2r_c)^2}{3\ (b \times t)\ (1-\mu_s)} \qquad (4\text{-}26)$$

where

- t = larger dimension of the column section
- b = smaller dimension of the column section
- μ_s = longitudinal reinforcement ratio of the column section
- r_c = radius of the edges of the section

4.3.2.3.2 Strengthening for Increasing Axial Tension

a- FRP systems with fibers oriented in a direction parallel to the axis of the member can be used to provide additional tensile strength of such members. Due to the linear-elastic nature of FRP materials, the tensile contribution of the FRP system is directly related to its strain level. The design tensile strength of FRP shall be limited by the ability to transfer stresses into the substrate through bond and the efficiency of anchoring the FRP layers at the ends.

b- The additional tensile strength shall be calculated using the following equation:

$$T_f = \frac{n\ t_f\ p_m\ \varepsilon_{fe}\ E_f}{\gamma_f} \qquad (4\text{-}30)$$

where

p_m = the total width of FRP laminates used to increase the tensile strength

c- The mode of failure of the tension member is controlled by the efficiency of the active bond length at the ends of the member. In order to prevent debonding in accordance with the method of anchoring given in Section 4-3-2-2-4, the value of the effective strain ε_{fe} in Equation 4-30 shall be conform to the value given in Equation 4-18 with the value of K1=1 instead of the value given in Equation 4-17a. The design bond length L_{ed} is taken equal to $2L_e$, where L_e shall be calculated using Eq. 4-16a. The design bond length shall be measured between the two ends of the tension member.

d- The effective strain in the tension member can be allowed to reach a value greater than that given in Equation 4-18 provided that its values shall not exceed the value given in Equation 4-31

$$\varepsilon_{fe} \langle\ 0.75\ \varepsilon^*_{fu} \qquad (4\text{-}31)$$

In such cases, the design bond length shall be calculated using Eq. 4-34 in order to prevent failure in the FRP and anchor regions. It should be noted that FRP shall be extended beyond the ends of the member by a distance equals to the design bond length.

4.3.2.3.3 Ductility Enhancement of Columns Subject to Flexure

a- The ductility of columns subject to seismic loads can be enhanced through confining the concrete section using FRP wrapping sheets with the fibers oriented in a direction perpendicular to the longitudinal axis of the column.

b- For the cases of seismic applications in which strengthening is limited to ductility enhancement of both circular and rectangular sections by providing FRP jackets at regions of maximum flexural stresses; such as at column-base joints and at beam-column joints and for a height of FRP jacket of not less that the thickness of the column. FRP jacket can also be provided at locations of splices of the longitudinal reinforcement of the column.

c- The confining effect of FRP jackets in seismic applications concerned with ductility enhancement shall be assumed to be negligible for rectangular columns with aspect ratios exceeding 1.5, or for columns having face dimensions exceeding 900 mm provided that the dimension of the section subject to maximum compressive stresses is less than 650 mm.

d- The maximum usable compressive strain in concrete ε'_{cuc} for FRP circular or rectangular members shall be evaluated using the following equation:

$$\varepsilon'_{cuc} = \frac{1.37\left(5\,f_{cuc} - 4\,f_{cu}\right)}{E_c} \qquad (4\text{-}32)$$

in which the value of f_{cuc} is taken from Equation (4-21)

The efficiency of the increase in ductility due to the use of FRP jacket shall be calculated using the equations presented in this section.

4-3-2-4 DEVELOPMENT, BOND LENGTHS, SPLICES AND DETAILING

4.3.2.4.1 General

This section presents requirements of development, bond lengths, splices and detailing of externally bonded FRP reinforcement. Such requirements depend on the geometry of the structure, the soundness and quality of the substrate, and the levels of load to be sustained by the FRP sheets or laminates. Many bond-related failures can be avoided by following these general guidelines for detailing FRP sheets or laminates:

a- The radius of the outside corners shall not be less than 13mm.

b- The lengths of the active bond length and the anchorage shall be taken according to Sections 4-3-2-4-4 and 4-3-2-4-6.

c- Sufficient overlap shall be provided when splicing FRP piles.

d- FRP sheets or laminates shall not be turned inside corners.

4.3.2.4.2 Distribution of Stresses along the Length of a Bonded FRP Laminate

The actual distribution of bond stress in an FRP Laminate is complicated by cracking of the substrate concrete. Figure (4-8) shows the general elastic distribution of interfacial shear stress and normal stress along an FRP laminate bonded to un-cracked concrete. It should be noted that the weakest link in the concrete-FRP interface is the concrete. The tensile strength of the concrete substrate will limit the overall effectiveness of the bonded FRP system. FRP debonding or concrete cover delamination could occur.

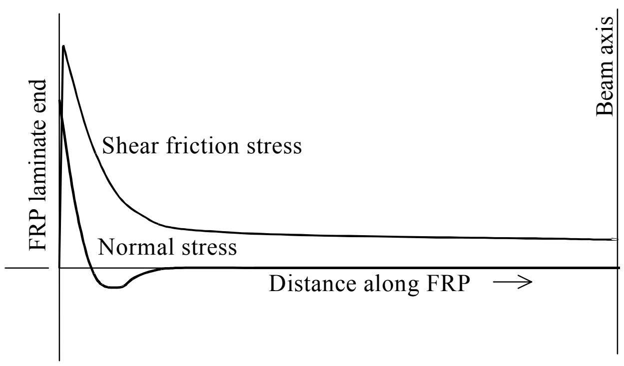


Fig. (4-8) Shear and tensile normal stress on concrete surface

4.3.2.4.3 FRP Debonding

FRP deboding of a brittle nature can result from the lack of bonded area of the FRP laminate to the concrete substrate. The increase of the interfacial shear and normal stresses lead to debonding of the FRP laminates accompanied by a thin layer of the concrete substrate. To prevent such a failure mode, FRP shall be extended to a distance equals to the design bond length L_{df} calculated according to Section 4-4-2-3-4.

4.3.2.4.4 Bond Length

The bond length for FRP shall be calculated based on the interfacial shear strength and the tensile strength at the FRP-concrete interface according to the following equations:

a- In case of using FRP laminates having a width equals to the width of the concrete section, L_f shall be taken from the following equation:

$$L_f = \frac{E_f \, \varepsilon_f \, n \, t_f}{0.24\sqrt{f_{cu}/\gamma_c}} \qquad (4\text{-}33a)$$

b- In case of using FRP laminates having a width less than the width of the concrete section, L_f shall be taken from the following equation:

$$L_f = \frac{b_{FRP}}{b_w} \frac{E_f \, \varepsilon_f \, n \, t_f}{0.24\sqrt{f_{cu}/\gamma_c}} \qquad (4\text{-}33b)$$

where

b_w = width of the concrete section subject to tension

b_{FRP} = effective width of FRP

c- Due to the brittle nature of the failures associated with debonding or concrete cover delamination, it is recommended to use a bond strength reduction factor equals to 0.5 when utilizing the methods available for calculating the bond stresses. The design bond length shall be calculated as follows:

$$L_{df} \rangle \, 2 L_f \qquad (4\text{-}34)$$

d- For members subjected to flexure, the design bond length is measured from the section subjected to maximum tensile stresses where the maximum moment acts as shown in Fig. 4-9. FRP shall be extended an additional distance equals to the anchorage length according to Section 4-3-2-4-6 and as shown in Fig. 4-9

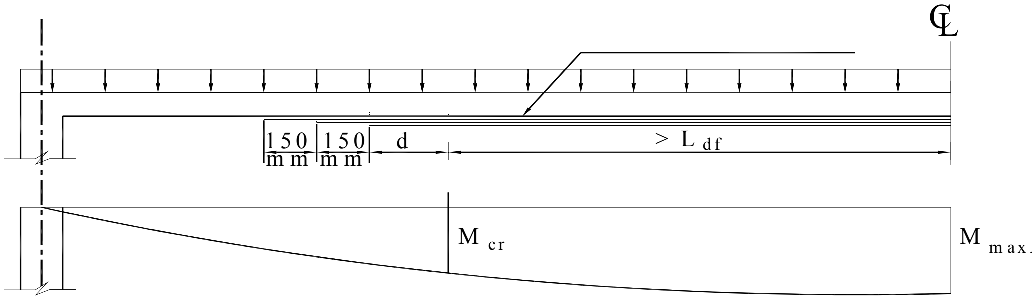


Fig. 4-9-a Termination of FRP laminates for simply supported beams

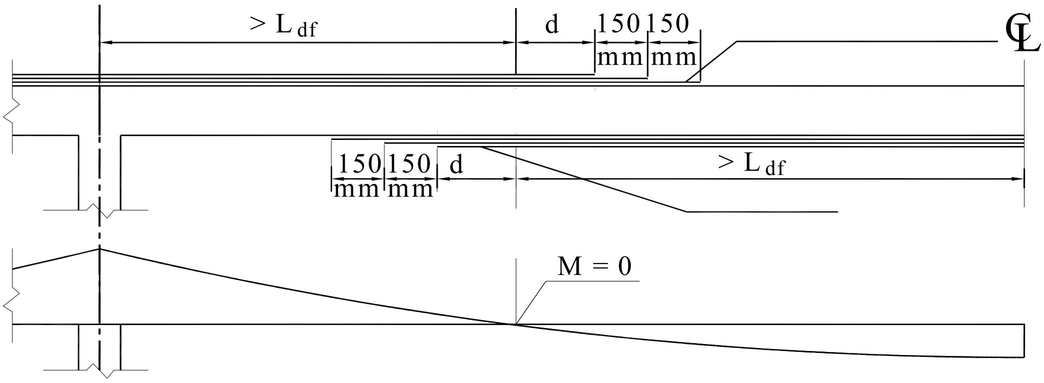


Fig. 4-9-b Termination of FRP laminates for continuous beams

Fig. 4-9 Termination of FRP laminates for members subject to bending moments

4.3.2.4.5 Delamination

Brittle concrete cover delamination (Fig. 4-10) results from the normal stresses developed in bonded FRP laminate (Fig. 4-8). As a result of this type of delamination, the existing reinforcing steel acts as a bond breaker in a horizontal plane. The result is the entire concrete cover layer splitting at the level of the tensile reinforcement. Such a brittle type of failure can be avoided by providing sufficient anchorage length according to section 4-3-2-4-6 in addition to using additional anchoring techniques at the ends of the FRP.

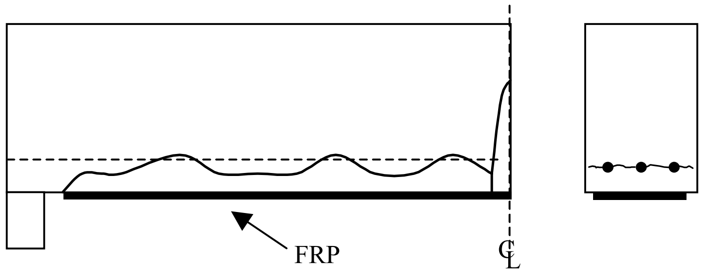


Fig. 4-10 Delamination caused by tension failure of the concrete cover

4.3.2.4.6 Anchorage Length

Concrete cover delamination can be controlled through controlling the level of stress at the termination of point of the FRP laminate. In case of not having accurate methods for analysis, the following general guidelines for the location of cut-off points for the FRP laminate can be used to avoid this type of failure:

a- For simply supported beams, the FRP laminates shall extend a distance greater than the depth of the beam, d, past the section subject to a bending moment equals to the cracking moment M_{cr} under ultimate loads, as shown in Fig. 4-9a. In addition, if the factored shear force at the termination point is greater than 2/3 the concrete shear strength, the FRP laminates shall be anchored with transversal U-shaped FRP wraps in order to prevent the concrete cover from splitting. Such U-shaped FRP wraps shall also be extended beyond the design bond length for a distance greater than the depth of the beam, d. In case of using multiple- ply laminates all plies shall not be terminated at the same section. Plies shall be terminated in steps with additional anchorage length such that the termination distance of the outermost ply is not less than 150 mm from the cracking moment section. Each successive ply shall be terminated no less than additional 150 mm as shown in Fig. 4-9a.

b- For continuous beams, a single-ply FRP laminate shall be terminated at a minimum distance, d beyond the inflection point (point of zero moment resulting from factored load). For multiple-ply laminates, the termination points of the plies shall be tapered. The outermost ply shall be terminated no less than 150 mm beyond the inflection point. Each successive ply shall be terminated no less than additional 150 mm as shown in Fig. 4-9b. These guidelines shall apply for positive and negative moment regions. In order to increase the resistance to the splitting of the concrete, FRP laminates could be anchored with transversal U-shaped FRP wraps.

c- Mechanical anchoring systems could be used to increase the efficiency of strengthening against concrete cover splitting as shown in the special anchoring methods in Section 4-3-2-4-9.

4.3.2.4.7 Detailing of Laps and Splices

a- Splices of FRP laminates shall be provided only as permitted on drawings and specifications, or as authorized by the engineer, as well as upon the recommendation of the system manufacture.

b- Sufficient overlap shall be provided to promote the failure of the FRP laminate before debonding of the overlapped FRP laminates.

c- Plies of FRP Jacket for columns shall not spliced at the same location. The length of the lap splice shall not be less than 200 mm in order to prevent jacket failure as shown in Fig. 4-11.

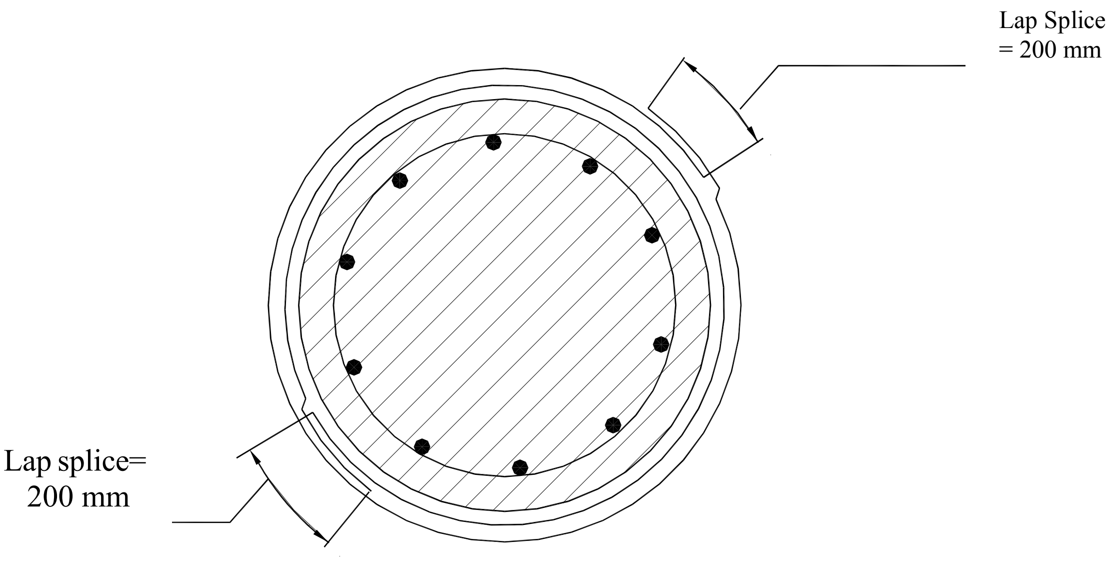


Fig. 4-11 Lap splices in columns

d- For unidirectional FRP laminates, lap splices shall be required only in the direction of the fibers. Lap splices shall not be required in the direction transverse to the fibers. FRP laminates consisting of multidirectional fabrics require lap splices in these directions.

4.3.2.4.8 Detailing Related to Humidity and Moisture Content

a- When using FRP, especially in full wrapping scheme, water might be concentrated at the lines of adhesion. It is recommended to provide gaps that permit the flow of vapor and moisture for the cases of flexural strengthening of beams and slabs.

b- In case of strengthening for shear, gaps at distances not more that 300 mm shall be left.

c- In case of strengthening columns, gaps of width from 30 mm to 50 mm shall be left between successive wraps 300 mm wide FRP wrap. The same procedure shall be applied at the joint between the Column and its base. Water shall not be permitted to flow between the substrate and the FRP laminates through closing the gap using a waterproof agent.

d- When dealing with the problems associated with moisture and water content, structures can be categorized as follows:

- Category one: structures located in dry environment with low water content such as internally protected members in buildings.
- Category two: structures subject to thawing and freezing in an environment with small water content such as protected structures located in open areas.
- Category three: structures located in wet environment such as structures located in open areas but not directly exposed to water or rains.
- Category four: structures located in an environment with high humidity or directly subject to water or those subject to high temperature accompanied by high humidity such as marine structures, bridges or dams.

Full wrapping schemes can be used for structures in categories one and two. Investigations on the condition of the surface shall be conducted in category three. Full wrapping scheme shall not be used in category four.

4.3.2.4.9 Special Anchoring Methods and its Detailing

a- Strengthening for Shear

In the cases of shear strengthening, it is not recommended to use FRP laminates bonded only to the two sides of the beam. For such cases it is preferable to anchor the fibers, if possible, along the full height of the compression zone of the beam through full or partial wrapping as shown in Fig. 4-12 and Fig. 4-13. In case of not having sufficient anchor in the compression zone, the internal lever arm shall be reduced in order to reduce the ultimate flexural strength as shown in Fig. 4-14. It is recommended to use this method only in case of not having other calculation method that is more reliable.

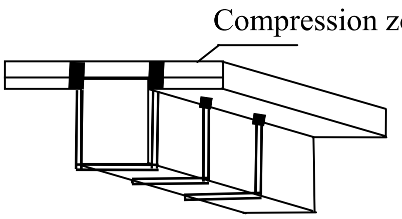


Fig. (4-12) Fixation in compression zone

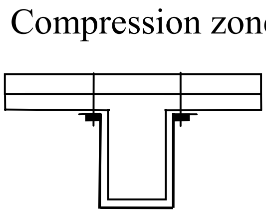


Fig. (4-13) Alternative method for fixation in compression zone

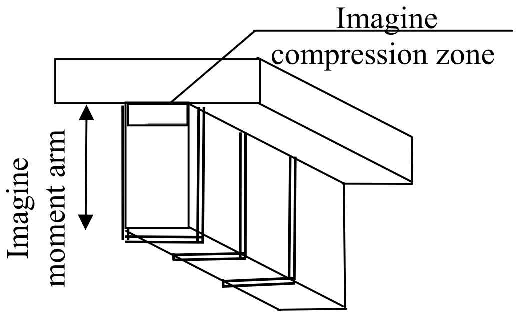


Fig. (4-14) Case of not enough fixation

b- Special Anchoring Systems for Increasing the strength against concrete cover delamination

1- It is recommended to use U-shaped laminates or L-shaped laminates or mechanical anchoring systems for the laminates (Fig. 4-15) or anchoring methods using FRP at the ends of the FRP laminates (Fig. 4-16) in order to resist the concentration of shear and normal stresses at the substrate that can result in debonding or concrete cover delamination.

2- When anchoring FRP laminates using bolts, it is important to make sure that its use shall not result in breaking the laminates.

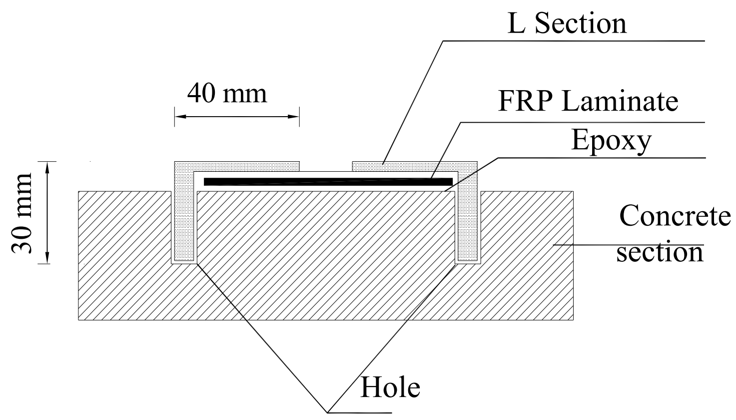


FIG. 4-15 MECHANICAL ANCHORS

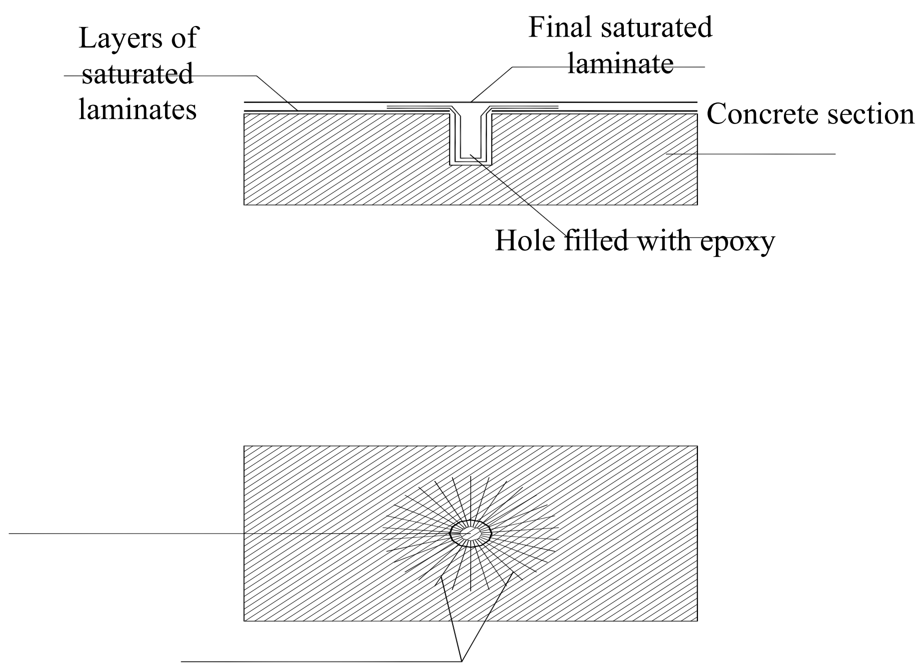


Fig. 4-16 FRP ANCHORS

4-3-3 Serviceability Limit States

4.3.3.1 Members Subject to Flexure

4.3.3.1.1 Requirements of the ECP-203

FRP Strengthened structures shall satisfy the requirements of the serviceability limit states of deflection and cracking of ECP 203 under service loads. The effect of the FRP external reinforcement on the serviceability can be assessed using the transformed section analysis.

In order to avoid inelastic deformations of the reinforced concrete members strengthened with FRP, the stress in the reinforcing steel in the strengthened section under service load, as per Equation 4-35 shall be limited to 80% of the yield strength.

4.3.3.1.2 Creep Rupture and Fatigue Stress Limits

a- The stress levels in the FRP reinforcement under sustained stresses shall be checked in order to avoid creep-rupture of the section strengthened with FRP. Such stresses can be computed by the using the elastic analysis in which the structure is assessed under the effect of all the permanent loads including dead loads and that portion of the live load that can be considered as permanent.

b- Members shall be considered safe against creep rupture if the developed working stresses are less than those computed using Equations 3-1, 3-2, and 3-3 of Section 3-5-8-2 of Chapter 3.

c- When the structure is subject to cyclic loads, the developed stresses shall be less than those computed using Equations. 3-1, 3-2 of Section 3-5-8-2 and 3-3 of Chapter 3.

4.3.3.1.3 Stress in Steel under Service Loads

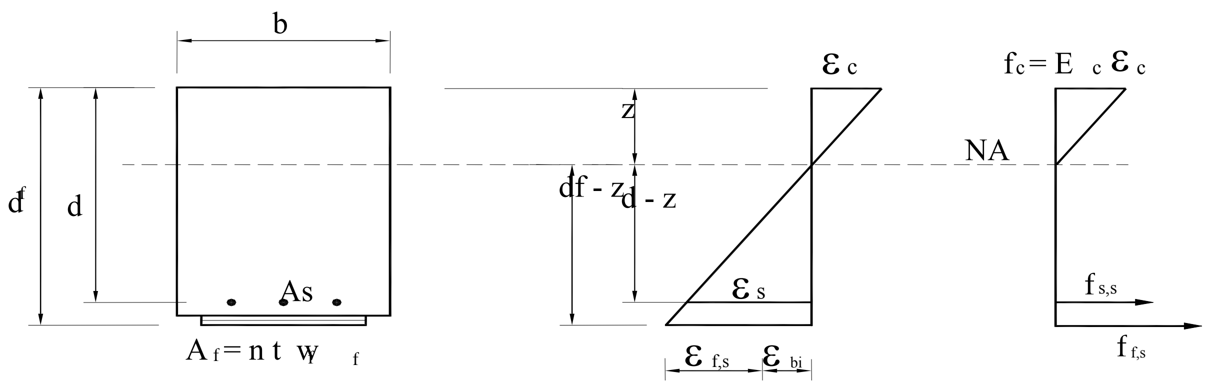


Fig. 4-17 Stress and strain distribution under service loads

d- The stress level in the steel reinforcement can be calculated based on a cracked elastic analysis of the strengthened reinforced concrete by using Equation 4-35. The bending moment, Ms is based on of all the permanent loads including dead loads and that portion of the live load that can be considered as permanent. (Fig. 4-17).

$$f_{s,s} = \frac{\left[M_s + \varepsilon_{bi} A_f E_f \left(d_f - z/3\right)\right] \left(d - z\right) E_s}{A_s E_s \left(d - z/3\right)\left(d - z\right) + A_f E_f \left(d_f - z/3\right)\left(d_f - z\right)} \leq 0.8 f_y \qquad (4\text{-}35)$$

Where,

z = the depth of the neutral axis at service loads

d_f = effective depth of FRP reinforcement

4.3.3.1.4 Stress in FRP under Service Loads

The stress level in the FRP reinforcement can be computed based on a cracked elastic analysis of the strengthened reinforced concrete section. The stresses developed in the FRP reinforcement under service loads, $f_{f,s}$ shall be computed according to Eq. 4-36.

$$f_{f,s} = f_{s,s} \left(\frac{E_f}{E_s}\right) \frac{d_f - z}{d - z} - \varepsilon_{bi} E_f \qquad (4\text{-}36)$$

The stresses developed in the FRP reinforcement shall not be more than the values given in Section 3-5-8-2.

4-3-3-2 Members Subject to Compressive Stresses

a- An FRP jacket produces passive confinement that becomes only effective at ultimate loads. Accordingly, it is important to ensure that transverse cracking in columns (cracking normal to the direction of loading) does not occur at service loads.

b- To ensure that transverse cracking will not occur under service loads, stresses in concrete under service loads shall be limited to 0.4 f_{cu} and the stresses in the reinforcing steel shall be limited to 0.6 f_y in order to avoid plastic deformation under sustained or cyclic loads.

c- Limiting the values of stresses in concrete and preventing cracking under service loads ensures maintaining relatively low stresses in the FRP jackets which in turn, guarantees avoiding creep-rupture failure.

d- In addition, axial deformation under service loads shall be investigated to evaluate their effect on the performance of the concrete member.

PART 4:

4.4 APPLICATION REQUIREMENTS FOR REPAIR AND STRENGTHENING WORKS:

4.4.1 Installation requirements

4.4.1.1 Application techniques

This part presents the installation techniques of FRP systems to strengthen concrete structures using the systems presented in part two of this chapter. This part also gives recommendations to choose the appropriate FRP system for a specific application.

4.4.1.1.1 Main method and application technique: Manual application

Strengthening with FRP mainly depends on the manual application of the laminate on the concrete element. FRP is attached to the concrete substrate using adhesive material, which consists of two components and is hardened without heating (usually epoxy base). This process shall be carried out according to the method and specifications given in this clause. Three factors shall be considered in the strengthening process as follows:

1- Strengthened surface (substrate):

The effectiveness of strengthening works depends on the type and properties of the concrete in the existing building, as well as on the surface condition on which FRP will be installed. Concrete surfaces shall satisfy the following conditions:

a- The surface shall be plane and free of any forms of defects, such as honeycombs, deformations and cracks. The surface shall be free of moisture, chlorides and sulfate ions.

a- Concrete properties at the surface shall satisfy the necessary requirements that insure the effectiveness of FRP strengthening works.

b- Concrete cover shall be free of carbonation and the steel reinforcement shall be free of rust.

2- Resin / Adhesive

The resin shall be a suitable material capable of adhering the FRP laminates to the concrete surface and satisfying the specifications and requirements of the project. The type of resin depends on the type of FRP laminates and surface condition. In addition, the resin shall be well saturated with the fibers in case of using wet lay-up type of application.

Table (4-3) : Basic properties of externally bonded FRP reinforcement

	Cured in situ (wet lay-up)	Pre-cured (prefab) strips
Shape	Sheets or fabrics	Strips
Thickness	0.1 - 0.5 mm	1 - 1.5 mm
Application	Saturated with resin and bonded to the concrete surface in situ	Prefabricated element is bonded directly to the concrete surface with resin
Typical application aspects	Sharp corners must be rounded	For plane surfaces only if not shaped during manufacturing
	Resin with low viscosity	Resin is thixotropic
	Consists of many layers	Consists of one layer, many layers may be added
	Require paste or mortar to prevent separation or debonding if bonded to uneven surfaces	Stiffness of strips and thixotropic resin allows for a limited unevenness in the concrete surface
	Flexible system in application, requires good quality control	Easy to use, good quality control is achieved for being prefabricated
Quality control	Good quality control should be insured. Incorrect or bad application will lead to debonding between FRP and concrete	

3- Fiber Reinforced Polymers (FRP)

Externally bonded FRP reinforcement is a composite material, as given in chapter (2). The two main types of FRP reinforcement are determined according to the type of application, as classified in section 4-2-4 of the second part of this chapter. Table (4-3) illustrates the basic properties for prefabricated strips or laminates "pre-cured" as well as sheets or fabrics cured in situ "wet lay-up".

4.4.1.1.2 Special Techniques:

Special techniques for FRP application are given in section (4-2-4-3). The code does not contain any specifications for these methods. Therefore, in case of using any of those techniques, experimental tests have to be carried out to ensure its effectiveness.

4.4.1.2 General Requirements for Application:

The following general requirements must be fulfilled for externally bonding FRP on the concrete surfaces:

1- Bonding FRP on the surface of the structural element may be applied in dry or wet weather. For each case, different requirements must be fulfilled in order to guarantee good bond.

2-It is preferable to apply FRP on a dry concrete surface. Humidity measurements on the concrete surface must be taken in order to ensure good bond between FRP and concrete.

3-In wet weather, precautions must be taken in order to ensure that the humidity of the concrete surface will not adversely affect the bond between FRP and concrete. It should be noted that humidity has bad effects on the strengthened members; since it causes corrosion of the internal steel reinforcement, which leads to spalling of concrete cover and eventually loss of bond between FRP and concrete. For the case of application in wet environment such as for underwater structures, special studies on the behavior and effectiveness of the application process must be made in order to ensure good bond between FRP and concrete.

4-The temperature of the strengthened structural element during application of FRP shall not be greater than the glass transition temperature of the resin, T_g. This temperature shall not exceed 45°C.

5-The following aspects shall be taken into consideration: temperature difference between FRP and concrete surface in service conditions, fire protection, ultra violet (UV) protection and the probability of premeditated destruction of strengthening works.

6-Corrosion of steel reinforcement as well as any defects in the structure and concrete surface shall be treated before applying the FRP strengthening system.

7-Strengthening applications shall be carried out in accordance with the specifications and requirements given in this part. The instructions given by the supplier and manufacturer of the resin, FRP and the system as a whole shall be taken into consideration. The application shall be carried out under the supervision of a specialist consultant. Documents of the project including specifications and design drawings approved by the engineer shall be considered by the consultant of the strengthening works. Quality control system shall be applied in accordance with the code requirements.

8-The application of FRP techniques shall be executed by qualified specialist contractors, who are trained and certified for such application.

4.4.1.3 Application of Repair and Strengthening Works

Repair and strengthening applications with FRP shall be carried out in accordance with the requirements of this section. The specifications of FRP materials and resins, given by the supplier and the manufacturer, shall be followed carefully provided that it shall not be in contradiction with the requirements of this section. Researches and experimental tests shall verify the requirements considered during application.

The application of bonded FRP as external reinforcement depends on the type of FRP (fabrics, laminates or prefab strips) as well as on the system of application as follows:

4.4.1.3.1 Repair Works before Application of Strengthening Works

Concrete has to be perfect, cohesive and has enough strength to be suitable for strengthening works. Any defects in concrete and its surface shall be treated first before the beginning of the strengthening works. It shall be ensured that no danger shall attack the existing structure due to rust of steel reinforcement. Therefore, repair works shall include the removal of rust and protection of the internal steel reinforcement using tested and relied methods before the beginning of strengthening works using FRP. Note that the use of FRP shall stop adverse effects such as continuation of rusting of steel reinforcement or water leakage or the presence of high percentage of chlorides.

The supplier and the manufacturer of FRP system shall be asked to provide information pertaining to the suitability of repair and retrofitting materials for FRP system, as following:

1- For bond critical applications, (section 4-2-3-1), safety and strength of the surface shall be checked and the tensile strength shall not be less than 1.5 N/mm2. If the tensile strength of the surface doesn't satisfy this value, a thin layer of concrete cover shall be removed to reach to the required strength. In case of existing deep damage in the concrete surface to the extent that the required tensile strength could not be achieved, these defects have to be treated using surface treatment methods, which may require concrete replacement in this parts. This replacement is done using ready-mixed mortars or grouts or new fine concrete with high quality. Full bond must be achieved between the treatment mortar and the concrete surface and the mortar surface shall be tested in order to satisfy the required tensile strength.

2- Although the external reinforcement gives partial protection to steel reinforcement against corrosion, the continuity of corrosion shall be prevented in order to avoid damage of concrete cover as a result of the corrosion of steel reinforcement, which shall lead to the loss of the strengthening efficiency, especially for bond critical applications. Accordingly, repair and protection of steel reinforcement shall be made in case the corrosion already exists. This could be checked by measuring the depth of carbonation and chloride content in the concrete cover. In addition, the chloride content shall not exceed the allowable values in the Egyptian code for design of reinforced concrete structures (ECP203).

3- Any cracks or structural casting separators with more than 0.2 mm width, which may cause water leakage, shall be injected with suitable and compatible low viscosity resin. The porosity of the concrete surfaces shall also be treated to decrease the corrosion potential of steel reinforcement.

4.4.1.3.2 Substrate Repair and Surface Preparation

4.4.1.3.2.1 Concrete Surface Preparation

Surface preparation requirements shall be based on the intended application of the FRP system. Applications can be categorized as bond-critical or contact-critical applications. The concrete surface shall be well prepared to satisfy full bond and required contact.

1- Roughness of the surface is required in order to keep the surface free of contaminations and weak material. This could be made using sand blasting, water jetting or grinding, to gain the maximum benefit of concrete quality. Manual or mechanical hammering (Scabling) could also be used for the concrete cover in case of weak concrete. For surface preparation using sand or water blasting, the prepared surface has to be similar to rough grinding with minimum large aggregate exposure. Most of wet lay-up systems require smooth plane surface as given in Table (4-4); therefore, emery would be suitable for this case. If mechanical preparation using jetting is used, this may require settlement mortar or post preparation and surface roughness paste. In case of water jetting preparations, surface reinforcement using FRP must be executed after drying of the surface according to the requirement No. 6. Generally, concrete shall not be damaged or destroyed regardless of the preparation method.

2- Concrete shall be cohesive, strong and free of defects and all types of effective damage. Deformed parts in the concrete, wide cracks and corners shall also be grinded and rust shall be cleaned.

3- Uneven surface may be allowed depending on the type of FRP reinforcement. Stiff prefab strips installed with a thixotropic resin with high viscosity, are less affected by uneven surfaces. While flexible laminates and sheets are more susceptible to damage when attached to uneven surfaces. Table (4-4) gives the allowable values of concrete surface deplaning.

Table 4-4 Permissible Unevenness of the concrete surface

Type of FRP external reinforcement	Permissible unevenness in 30 cm length (mm)	Permissible unevenness in 2 m length (mm)
Prefab strips with thickness > 1 mm	**4**	**10**
Prefab strips with thickness < 1 mm	**2**	**6**
Cured in situ wet-lay up system	**2**	**4**

4- Due to the importance of having an even concrete surface before bonding the FRP laminates, putty or mortar shall be used with the resin in the wet lay-up systems. This putty shall satisfy the requirements of concrete repair products. The used putty shall also satisfy all specifications and stipulations of the manufacturer and the compatibility of resin and putty with tissues pasting shall be proved.

5- Prepared surfaces shall be cleaned and free of dust before the execution of strengthening. This could be done using air suction or air pressure free of oil.

6- Prepared surfaces shall be dry and the maximum allowable humidity in concrete surface, specified by the system manufacturer, shall be observed. Some resins could be used in moist conditions; however, the concrete surface shall not be wet anyway. The concrete surface temperature shall be greater than the dew point with at least 5^{o}C. The dew point depends on the relative humidity and temperature. If this condition is not achieved, ventilation shall be made and temperature shall be modified (may be by heating).

7- Marks shall be made on the concrete surface at the intended locations of external FRP reinforcement. For FRP wrapped around the corners of rectangular cross sections, the corners shall be rounded with a radius according to the design drawings. For required mechanical anchorage, preparation works shall be executed in the appropriate manner.

8- Primer shall be applied to all areas on the concrete surface the intended locations of external FRP reinforcement. The primer shall be placed uniformly on the prepared surface at the manufacturer's specified rate of coverage.

4.4.1.3.2.2 Preparation of Fiber Reinforced Polymers (FRP)

a- Prefab Strips

Prefab strips shall be delivered to the location with the required breadth and thickness and shall be cut according to the required lengths as specified in the design drawings. Strips shall be free of adhesive contaminations such as grease, carbonized dust, shuttering oils, etc. For sheets with built-in masking tape, this tape shall be removed directly before execution without touching the surface of the strips. Other strips may require grinding and cleaning before usage in order to ensure good conditions of the strip surface and good bonding with the concrete. Strips shall be handled with gloves and in dry conditions. No damage of the FRP strips shall occur during transportation, handling or cutting. They also shall not be twisted, bended, curved or crooked.

b- Wet Lay-Up Type

Wet lay-up laminates shall be cut according to the required lengths as specified in the design drawings and shall be free of any contaminations. Laminates shall not damage during transportation, handling or cutting. Cover and protection layers shall be removed just before usage and installation. Specifications, instructions and precautions of system manufacturer shall be followed carefully. Laminates shall also be free of twisting and fiber strings should be oriented correctly.

4.4.1.3.3 Installation of FRP External Reinforcement

The installation depends on the type and system of FRP external reinforcement. For prefab strips, resin is used for attachment on the concrete surface only and the resin type shall be thixotropic. While for wet lay-up system, resin must be saturated in laminates, as well as for attachment on the concrete surface. The resin shall have low viscosity, yet enough for attachment on the bottom surfaces of the elements such as beams and slabs. Installation of FRP external reinforcement must satisfy the specifications given in this clause supported by quality control tests mentioned in this code. All the specifications, recommendations and precautions given by the manufacturer of the system such as ambient temperature, surface condition, relative humidity, ratios of mixing components, mixing time, working validation time after mixing, and safety measures shall be followed. Application of the material shall be finished within 80 percent of its pot life, in addition sufficient time shall be given for splices. After application, the surface shall be plane to prevent separation of FRP from the concrete surface. The variation in the depth of the surface within 30 cm length shall not be more than 4 mm in prefab strips and 2 mm in wet lay-up systems.

4.4.1.3.3.1 Prefab Strips and Laminates

The resin is applied on concrete surface as a thin layer just after mixing. The resin shall also be applied on the FRP sheet as an arch shape (for 100 mm sheet width, maximum resin thickness is 5mm). To avoid having voids between the sheet and the concrete substrate, the sheet shall be placed on the surface and pressed against the concrete with a rubber roller to ensure full contact with the concrete. Additional resin shall be squeezed out of the sheets sides by pressing from the middle of the sheet to the edges. The final resin layer shall be uniform and equal to 1.5 to 2 mm. Usually, the sheets are applied using 1 layer, however, multi-layers could be used (not more than three layers for prefab sheets unless tests are carried out on more number of layers). At intersections between sheets, resin thickness shall be increased gradually before and after intersections to cover the requirements given in Table (4-4). If masking tape is put on the concrete either side of the strip before gluing, the adhesive surplus can be removed more easily.

4.4.1.3.3.2 Wet Lay-Systems

It is usually required to use a primer and putty on the concrete surface to achieve even surface according to specifications given by the system manufacturer. Low viscosity resin shall then be applied on the concrete surface using a roller or a brush. This process is called “undercoating”. Then, the sheets are applied by manual pressing onto the resin such that it is stretched without having voids. Impregnations of the sheets are performed by applying resin on top of the sheet with a roller brush (after removing the paper backing, if present). This process is called “overcoating”. The final bond line shall have an even thickness along the sheet.

In order to obtain higher level of quality control, the sheets can be impregnated with the resin in a saturator machine. In this method, a better-controlled resin rate with a more uniform thickness can be applied. This method is called automated saturation. The pre-saturated sheet is then applied on the concrete surface, which is free of pores. Multi-layers could be done before the hardening of previous layers (no more than 5 layers are applied if not proved with tests). There is no need to apply external pressure on the sheets during hardening and drying.

4.4.1.3.4 Surface Finishing

For architectural purposes, a certain type of finish may be required. In order to protect the FRP system against fire, UV radiation, damage or vandalism, finishing layers are crucial on the long-term integrity of the system. Finishing layers may be applied using several number of coats, shotcrete or fire protection sheets. These types of finishes shall be applied according to the specifications and recommendations of the manufacturer. Finishing layers shall be compatible with the FRP system. If heat is required for applying the finishing layers, this shall not damage the system.

4.4.2 Qualification of Contractor

4.4.2.1 A qualified contractor with sufficient experience shall execute the strengthening and repair works of concrete including application of FRP systems and preparation of the concrete surface. This is because of the nature of these works, which mainly depends on the accuracy and good quality of execution. This finally affects the structure safety and economies of the system.

4.4.2.2 The contractor shall present the documents, which indicate his qualifications to accomplish these works, to the consultant representing the owner. According to these documents, the owner could decide if the contractor is qualified for such work. These documents include:

a- A list of the previous works in the field of repair and strengthening with FRP systems.

b- A list of previous works in the field of repair and strengthening of RC structures.

c- Training courses certificates of application of these systems.

d- Recommendation letters from clients or consultants certifying the completion of similar works.

4.4.2.3 The execution of the work on site shall be carried out by qualified technicians trained for such projects. The contractor shall be responsible for training his workers and update them periodically due to the continuous development in this field.

4.4.2.4 It is preferable that technicians and workers be trained on the same type of the used system in an authorized training center by the supplier of the system.

4.4.2.5 The supervisor on site shall be qualified and have good knowledge with FRP systems, application, curing, environmental conditions for working.

He shall also be aware of measures for accepting the work, and shall be present at all times of execution.

4.4.2.6 The safety supervisor shall be aware of the safety precautions for storing, handling and use of the materials according to specifications and instructions of the manufacturer. He shall also be aware of the probable danger and emergency instructions that should be followed in case of accidents.

4.4.3 Inspection, Evaluation, Acceptance and Quality Control

4.4.3.1 General Considerations

4.4.3.1.1 This part discusses the quality control and quality assurance for strengthening and repair of RC elements using FRP systems, as well as preparation of concrete surfaces to be ready for applications of these systems. This shall be done in steps in order to ensure the quality of materials, applications as well as recommendations for design and execution given in this code and specified by the designer. This section also introduces the steps that shall be followed for monitoring and inspections and the required tests for executing the quality plan. It also defines the standards for accepting the executed works.

4.4.3.1.2 The definitions given in the Egyptian code of practice for design and construction of RC structures, (ECP203) regarding the quality control of reinforced concrete works shall be followed.

4.4.3.1.3 Quality control for repair and strengthening works using FRP systems shall be carried out according to the following:

a- Internal Quality Control:

This shall be carried out by specialized engineer with sufficient experience, who is usually responsible for the project execution. A specialist may be needed in monitoring, inspection and quality control. The specialist shall be provided with all documents and facilities to complete his job.

b- External Quality Control

This shall be carried out by an external authority, which has no relation with the internal quality controller of the project. This shall include revision of the project documents, periodic inspection, performing special tests on materials, if needed, as well as scheduled and unscheduled inspection on execution.

4.4.3.1.4 A qualified engineer with good experience in the field of FRP systems and quality control procedures shall perform the monitoring, inspection and acceptance of executed works.

4.4.3.1.5 The monitoring and technical inspection shall be defined in the contract documents of the project, including detailed illustrations for operations and steps of quality control.

4.4.3.1.6 For strengthening RC structures with FRP, inspection and monitoring works shall be executed in a number of stages as follows:

A- Pre-execution stage: at which the project documents shall be delivered and revised and the materials shall be accepted.
b- Execution stage: at which the surface preparation, application of FRP systems up to hardening, protected finishing layers and required tests shall be executed.
c- Post-execution stage: at which the inspection of the executed work shall be carried out as well as periodic inspection during life time of the structure to observe any defects in the strengthening works and make the necessary corrections as discussed in section 4-4-4.

4.4.3.1.7 Tests for quality control and material acceptance shall be performed by an authorized laboratory by the owner (represented by the consultant). The laboratory shall have the required equipments and experience to perform the quality control tests for FRP materials.

4.4.3.2 Definitions

The given definitions in the Egyptian code of practice for design and construction of RC structures (ECP 203), are referenced as follows:

4.4.3.2.1 Quality Assurance

Quality assurance is considered as an administrative tool: It is a group of regulations, plans and programs necessary to ensure that the structure will satisfy its function.

4.4.3.2.2 Quality Control

Quality control is considered as a production machine: It is a group of operations related to the physical, mechanical and chemical properties of materials, methods and services, which are introduced as a measurement tool.

4.4.3.2.3 Quality Assurance System

It is an administrative control system, which regulates the promises, relations, responsibilities and requirements of the owner. It is recorded by quality assurance plan, included in the quality assurance program to introduce tools affecting the activities and requirements of the project.

4.4.3.2.4 Quality Assurance Plan

It is a project plan prepared and specified by the owner with the aid of the consultant or a quality control engineer. This plan contains the owner affairs and quality target of the project. Detailed illustration of the work method of statement and regulating actions, which ensure that the project will begin with a system plan, shall be followed by all parties. The quality assurance plan is considered as a high level document in total quality assurance.

4.4.3.2.5 Quality Assurance Program

It is a document illustrating the affairs, actions and work methods and complies with the quality requirements and contract documents.

4.4.3.2.6 Internal Quality Control

Internal quality control shall be continuously performed to ensure achievement of the requirements and shall be carried out by specialists. The person, who is responsible for execution of the quality control plan, is usually one of the project team. However, in case of insufficient experience of the engineers working in the project, specialists shall be hired to supervise the internal quality control works.

4.4.3.2.7 External Quality Control

External quality control is performed by external authorities, who have no relations with the internal quality control authorities of the project. This part of external quality control includes revision of the structural design, periodic examinations and special tests on materials if needed. Unscheduled and periodic inspection on the project shall also be also included.

4.4.3.2.8 Role of Quality during Lifetime of the Project

Quality control and assurance are integrated operation, which starts with the feasibility study of the project and continues with the design, execution and delivery stages. It is also continued during the use of the structure as given in the Egyptian Code for design and construction of reinforced concrete structures (ECP 203).

4.4.3.3 Technical Inspection

4.4.3.3.1 Inspection

The inspection is the preparation of a program to ensure that the materials and systems used in the repair or strengthening of the concrete elements are fulfilling the requirements given in that code and contract documents

4.4.3.3.2 Internal Inspector

The internal inspector shall be qualified more than those who supervise the inspected activities. Qualifications of the inspector shall be documented as well as the program by the consultant.

4.4.3.3.3 External Technical Inspector

The external inspector shall work for the owner, consultant, any certified authority or governmental agency responsible for quality control in the construction industry. The external technical inspector shall not work for the contractor or the internal quality control inspector. The choice of the technical inspectors for external monitoring shall be based on their experience, fairness and their affirmative opinions.

4.4.3.4 Testing laboratory on Site

The need of the testing laboratory on site shall be specified in the contract. The equipments depend mainly on the size of the project and the required degree of control. Tests are permitted to be performed by other specialized laboratories, which shall be selected by the consultant and specified in the project documents.

4.4.3.5 Quality Control Stages

Quality control, monitoring and inspection for strengthening and repair work with FRP systems shall be performed in a number of stages, as follows:

a- Pre-execution stage: at which the project documents are delivered and revised and the materials shall be accepted.

b- Execution stage: at which the surface preparation, application of FRP systems up to hardening, protected finishing layers and required tests shall be executed.

c- Post-execution stage: at which the inspection of the executed work shall be carried out as well as periodic inspection during life time of the structure to observe any defects in the strengthening works and make the necessary corrections as discussed in section 4-4-4.

4.4.3.6 Quality Control Stages and Pre-Execution Inspection

4.4.3.6.1 Receiving and Revision of Project Documents

The following documents shall be made available in order to be able to carry out the internal quality control monitoring and external and internal inspection before commencement of strengthening and repair work with FRP.

a- Drawings of the strengthening works.
b- Specifications of the project.
c- Specification of all supplied materials used in the project and a certified data sheet of the materials.
d- Detailed illustration of the application technique including preparation of the concrete surface, application and curing of the materials and protection method. The used tools shall also be identified. Handling and storage of the materials as well as safety instructions of the use of the materials should be clarified.
e- Monitoring and quality control program for execution, defined by owner (represented by the consultant), including methods of executing the quality control plan.
f- Certificate for acceptance of the supplied material.
g- Qualification certificates of the contractor, who shall be responsible of the execution of the strengthening and repair works, workers and safety.

4.4.3.6.2 Revision of Structural Design

It is a basic stage for inspection, which includes review of the original structural design and verifying the dimensions from site and review of structural evaluation reports. Review of the repair strengthening works shall also be revised. Execution shall not begin until revision of the structural design according to the recommendations of this code is accomplished. Structural work for strengthening shall not be in contradiction with any of the other engineering documents of the project, such as architectural, air conditioning, and sanitary work.

4.4.3.6.3 Primary Inspection

The primary inspection is carried out to evaluate the internal quality control laboratory tests according to the code requirements and project specifications. A site visit shall be made to carry out a visual examination of the concrete elements required to be strengthened or repaired. Storage places and materials storing conditions shall be identified.

4.4.3.6.4 Technical Inspection of the Materials

4.4.3.6.4.1 Before commencement of the strengthening and repair works, the inspector shall ensure that the supplied materials on site are identical to these composing the designed FRP system and specified by the consultant. The consultant shall also define the acceptance standards of monitoring and quality control works.

4.4.3.6.4.2 The supplier shall provide the certificates of all supplied materials, including the characteristic properties of filling polymers, resins and fibers / laminates / sheets as well as protection layers. Production date and expiration period of polymers shall also be indicated. The inspector shall ensure that the properties given in the certificates and submitted by the contractor are identical with those of the supplied materials, specification of the project and that the polymers have not expired.

4.4.3.6.4.3 The mechanical properties of the laminates and fibers shall be introduced by the supplier. Key properties of the materials, such as tensile strength in addition to other properties specified by the consultant, shall be verified by additional testing. Test shall be performed on a number of specimens representing the supplied quantity and shall be sent to an authorized laboratory before execution with enough period of time. This shall be made according to section (2-5).

4.4.3.6.4.4 If the test results failed to give the minimum requirements defined by the consultant, the supplied material shall be rejected.

4.4.3.6.4.5 The storage condition of the materials shall be identical to that given in the instructions provided by the manufacturer / supplier and agree with the operation of handling and storing of polymer materials.

4.4.3.6.5 Material Approval

4.4.3.6.5.1 Resources Approval

The material suggested resources shall be approved by the technical inspector in order to be sure that these materials fulfill the project's requirements. This approval shall be provided along with, test results from authorized laboratories.

4.4.3.6.5.2 Acceptance According to Product Certificate

In some cases, in which the material is supplied from known resources, which have good experience in such works, materials shall be approved according to product certificates. The certificates shall be accompanied with all necessary data such as test results of quality control at production location and at authorized laboratories. However, this does not mean to eliminate the periodic tests or any additional tests according to the requirements of the external inspector.

4.4.3.6.5.3 Material Rejection

If the material does not fulfill the code requirements or project specifications, it shall be rejected. The rejected material shall be removed from storage location and from site. For some cases, if there is not enough confidence in the test results, repeating the tests are acceptable. For such cases, tests on two separate specimens shall be carried out. The two specimens shall pass the test. The final report shall include the first result showing failure of the specimen and the results of the repeated tests.

4.4.3.7 Monitoring and Quality Control of Execution

The quality control engineer as well as the technical inspector shall be present on site during execution of work to perform the following:

a- Approving of the supplied materials according to the Egyptian code of practice.
b- Approving of the supplied materials according to specifications and design drawings of strengthening and repair, as given in section 4-4-3-2-2.
c- Approval of the surface preparation according to code requirements and specifications of the supplier/manufacturer and approved by the designer.
d- Ensuring that the required quantity of fibers and polymers are available for one day before execution.
e- Monitoring the mixing process of polymers and resins and ensure that the quantities, ratios and time of mixing are correct, in addition, to monitoring the impregnation and application of FRP system.
f- Observing the applied FRP laminates in terms of number and thickness of layers and fiber orientation.
g- Ensuring that the specifications of the code or that given by the designer or manufacturer are followed. For example, no contact between the carbon fibers and steal reinforcement or any other metal parts shall take place.
h- Preparing the specimens required for testing
i- Ensuring hardening of the applied FRP system.
j- Observing all strengthened elements after work completion by visual observation or any other method.
k- Observing existing defects and compare them with the acceptable standards.
l- Monitoring the repair work of the defected parts in the applied systems (if exist).

All monitoring, inspection and evaluation works shall be reported daily. Check list shall be prepared in which completed works and its conditions shall be reported.

4.4.3.7.1 Monitoring, Quality Control and Technical Inspection for Surface Preparation.

4.4.3.7.1.1 The quality control engineer as well as the technical inspector shall ensure the application of the surface preparation steps, as given in the project's specifications and agreed upon with the manufacturer/supplier instructions.

4.4.3.7.1.2 The surface preparation shall agree with the work specifications given in section 4-4-1-3-2 of this code.

4.4.3.7.1.3 Pull-off tests shall be performed to measure the bond strength between the resin and the surface. This shows the surface condition and the bond between the concrete and FRP system. The test also gives an indication of the quality of the surface preparation.

4.4.3.7.2 Acceptance of the Substrate before FRP Application

The acceptance standards for the prepared surfaces to apply the FRP system are determined by the designer and specified in the project's specifications. They must agree with the minimum limits given in section 4-4-1-3-2 of this code. In case that the latter limits are not achieved, no strengthening system shall be allowed on this surface.

4-4-3-7-3 Monitoring, Quality Control and Technical Inspection During Application of FRP System

4.4.3.7.3.1 The monitor shall record the ambient temperature and humidity level on the surface of the element required to be strengthened on the day of execution. He shall ensure that those values do not exceed the values listed in the material instructions.

4.4.3.7.3.2 Resins mixing operation shall be followed as well as the mixing ratios, whether by volume or by weight, as listed in the supplier instructions. The mixing method (manual or mechanical) as well as the mixing time shall be also observed. The quantities of each component prepared for mixing as well as the expiry date shall to be checked.

4.4.3.7.3.3 The sheets shall be saturated before placing on the strengthened element.

4.4.3.7.3.4 Placing of the sheets on the strengthened element shall be compatible with that required and illustrated in the project documents. Number of layers, thickness, fiber orientation, dimensions and development length shall be checked. Full adhesion between the sheets and the concrete surface shall be checked to ensure that no voids exist underneath the sheets.

4.4.3.7.3.5 The hardening operation shall be observed as given in section 4-4-3-7-4. Coating or protective layers shall be executed according to the supplier instructions.

4-4-3-7-4 Monitoring, Quality Control and Technical Inspection for Curing and Hardening

4.4.3.7.4.1 The quality controller as well as the technical inspector shall monitor the amount and rate of hardening of FRP systems after application. The ambient temperature and humidity level shall also be observed until full hardening of the FRP system. All items shall be checked according to the supplier or manufacturer instructions and approved by the consultant and given in the project specifications.

4.4.3.7.4.2 Hardening of polymers shall be checked by visual inspection including the samples executed in the field. Laboratory tests may be applied for small samples of resin or saturated sheets if required by the consultant.

4.4.3.7.4.3 The strengthened parts shall be covered in order to be protected from environmental conditions until full hardening.

4.4.3.7.5 Inspection and Evaluation Reports for Execution of Strengthening Works

The engineer who shall be carrying out the inspection and evaluation shall prepare a daily report including the following:

a- Date and time of installation.
b- Temperature and humidity level and general weather observations.
c- Temperature and humidity level of the surface.
d- Surface preparation methods and resulting profile.
e- The condition of the element required for strengthening or repair in terms of smoothness, dryness of surface and presence of voids or cracks.
f- Cleanliness of the element surface to ensure having no dust, grease or oil.
g- Recording of packing numbers of resins and fibers supplied to the site for use in that day.
h- Quantities of mixed resins, mixing ratios, time of mixing, method of mixing and its compatibility with the project specifications. Remarks about shape and color of polymers during application shall also be recorded.
i- Compatibility of the installation method with the specifications and supplier instructions.

j- Progress of curing rate, uniformity and efficiency.
k- Number of samples executed in the field, its preparation and testing in the laboratory.
l- Type of coating or protective layers.
m- Observation and examination of completed work and field tests.
n- Observations of any defects in the executed work.
o- General remarks of work.

4-4-3-8 Evaluation Tests for Quality Control and Assurance During Installation

4-4-3-8-1 Tests of Cured and Applied Systems in the Field

Samples shall be prepared during installation in the same environmental conditions such as temperature, humidity level and other weather conditions using the same materials and workers. Samples shall be sent for testing in an authorized laboratory, where a number of the longitudinal laminates shall be cut for testing under axial tension. All samples shall have a tensile strength not less than that specified by the designer. When a sample fails to meet the minimum required tensile strength, other samples shall be tested. If the other samples fail to meet the required strength, another sample prepared in the same day shall be sent for testing. All samples shall meet the minimum required strength as a requirement for accepting the work. If the tensile strength is not achieved, the installed work should be rejected and removed.

4-4-3-8-2 Tests of Pre-Saturated and Pre-Cured Systems

Samples shall be prepared during installation of FRP in the field and shall be sent for testing in an authorized laboratory. All samples must achieve the minimum required tensile strength specified by the designer as a requirement for acceptance of the executed work. If the strength is not achieved, the executed work shall be rejected and removed.

4-4-3-8-3 Field Tests

The designer may ask to perform field tests such as polymers tests or pull-off test to examine the bond strength. Core test may be required to ensure that the executed number of layers and its thickness meet the design requirements. The inspector shall witness the tests at the specified locations determined by the consultant. He shall prepare a report including the results of these tests. If these tests do not fulfill the design requirements of the project, repair work shall be performed according to the consultant recommendations.

4-4-3-8-4 Non-Destructive Tests

Non-destructive tests shall be performed upon the designer's recommendations or if the visual examination indicated the presence of problems. Tests may be needed to determine the presence of internal voids, delamination or debonding of sheets, such as acoustic hammer sounding, ultrasonic and thermography.

4-4-3-8-5 Pull-off Test

Pull-off test shall be performed in cases at which the test results do not fulfill the required specifications or in case of having doubts in the mechanical properties or bond strength of the executed work. This test is considered as a destructive test; therefore, it shall be performed on parts which have minimum stresses. The number and locations of the pull-off tests shall be specified by the consultant. The test shall be performed on the FRP systems applied on the concrete element after hardening. Accepting criteria of test results shall be determined according to the specifications of the designer and the project consultant.

4-4-3-8-6 Load Tests of Concrete Elements After Repair or Strengthening

This test is performed if listed in the project specifications or in case of having doubts in the efficiency of the strengthening work. Loading test is performed on elements such as beams or slabs after strengthening by FRP after enough time for the FRP system to reach its design strength. The test shall be performed according to the requirement of the Egyptian code of practice for design and construction of reinforced concrete structures (ECP 203).

4-4-3-9 Technical Inspection Work After Installation, Defects Evaluation and Repair Suggestions

4.4.3.9.1 Executed works shall be visually examined to observe any defects or non-uniformity. The surface shall be hammered lightly to check any separation of layers or using any other method, which could determine any separation areas more than 13 cm^2. These methods shall have no effect on the applied system such as ultrasonic or thermography.

4.4.3.9.2 The existing defects shall be compared with the accepting criteria specified by the consultant. As a result, the installed work shall be accepted or repair suggestions shall be presented. The inspector shall observe the execution of these works to ensure that it is done properly.

4.4.3.9.3 Common standards for evaluating the defects of FRP systems saturated on site and externally bonded are as follows:

- Defects such as layers delamination with small areas not more than 13 cm^2 shall be permitted if not exceeding 5 % of the total strengthened area and not repeated more than 10 times in 1 m^2.
- The presence of large delamination between layers or between layers and concrete surface with areas more than 160 cm^2 can affect the performance of strengthening system. In this case, it shall be removed and replaced by equal number of layers with the same type and fiber orientation and ratios.

4.4.3.9.4 Delamination between layers or between layers and concrete surface with areas less than 160 cm^2 could be repaired by epoxy injection. Other suitable resins may be also used for filling the voids. Replacing the unbonded layers with equivalent areas of FRP may also be used.

4-4-4 Maintenance, Observation and Repair of Strengthening Work with FRP

4-4-4-1 General

4.4.4.1.1 FRP systems installed to strengthen or repair structural elements are exposed to damage or deterioration similar to other materials. This may be due to vandalism or bad handling during transportation or application. It may be also due to overloading or exposure of strengthened element to impact load or negative effect due to environmental conditions.

4.4.4.1.2 Deterioration of FRP systems are due to the presence of cutting or voids or changing of the fiber orientation or changing of the resin properties. This will affect the mechanical properties of the applied material such as strength, bond, and adhesion strength with the strengthened structural element as well as its durability.

4.4.4.1.3 This part discusses the periodic maintenance recommended for elements strengthened by FRP systems. Determination of defects, its repair and accepting criteria are also included.

4.4.4.1.4 Periodic observation must be performed for all strengthening and repair work under the effect of different acting loads and for a sufficient time specified by the consultant, as given in clause 4-4-4-3. The observation shall be based on the nature of the project, its importance and the amount of the executed works.

4.4.4.1.5 All repair works should be performed according to the supplier/manufacturer recommendations after the approval of the designer to ensure that they do not affect the safety and efficiency of the system.

4.4.4.1.6 Tests that are needed for evaluation and acceptance must be operated in specialized and qualified laboratories.

4.4.4.1.7 Safety instructions shall be followed carefully during transportations, storage and handling of repair materials due to the sensitivity and danger of some of theses materials. The excess materials shall be removed away.

4-4-4-2 Periodic Maintenance and Observation Works

4.4.4.2.1 Observation of all strengthening and repair works with FRP systems must be performed on periods specified by the designer, to observe any deterioration of these systems and suggest its repair scheme.

4.4.4.2.2 All observations shall be recorded in terms of reports and be kept for reference.

4.4.4.2.3 The observations shall be performed by means of visual inspection for the strengthening work after cleaning of dust, oil, and grease using water or suitable organic dissolvent. Any remarks for changing in color, cracks, voids, sheets delamination, buckling or obvious deformations shall be recorded and informed to the designer to evaluate its effect on the strengthening system.

4.4.4.2.4 Some non-destructive tests shall be performed upon the designer's requirement or if the visual examination indicated presence of problems. Testes are needed to determine the presence of internal voids which are not visible or delamination of sheets. These non-destructive tests are acoustic hammer sounding, ultrasonic and thermography. Pull-off test or loading test may be required for specified parts.

4-4-4-3 Periodic Observation for Repair and Strengthening Works

4.4.4.3.1 Periodic observations are performed on the concrete structure according to the importance of the project as a whole or some of its elements that were strengthened or repaired by FRP systems. This is done to record the actual structural behavior for these elements after strengthening or repair under working loads and different environmental conditions and to ensure that they fulfill the design requirements and structure safety and strength.

4.4.4.3.2 Observations shall be made for a sufficient period of time specified by the consultant according to the nature of the project, its importance and the amount of executed work.

4.4.4.3.3 Many systems of observation could be used with large difference in technical and human requirements according to the cost and the level of technology. The project consultant shall be responsible for the choice of suitable observation system according to the nature of the structure, its importance, usage and the effect of negative factors as well as the amount of executed work.

4.4.4.3.4 The project specifications shall contain the observation system of the strengthening or repair work, including technical details such as description of instruments used in observations, observation points, frequency of measuring data. The contents and time schedule of the technical reports shall also be included.

4.4.4.3.5 Any observation system shall include the following:

- Sensory system
- Data acquisition system
- Data processing system
- Communication system
- Damage detection and modeling system

4-4-4-4 Damage Evaluation and Acceptance Standards

4.4.4.4.1 Based on observations and tests performed on FRP systems, damage shall be evaluated to determine its effect on the strengthening system of the structure, its safety and durability.

4.4.4.4.2 All steps in section 2-5-2-3, which illustrate the limitation of the permissible defects for delamination of sheets of FRP shall be covered. The required decision for repair shall also be included.

4.4.4.4.3 The supplier/manufacturer shall provide the acceptance standards of the system. The standards must be followed if it is more severe than the previously given values.

4.4.4.4.4 The consultant carrying out the evaluation and repair of the FRP system may require more stringent standards to accept the defects or damage. It shall be based on the review of the original design, reports during installation or the condition of the structure and its use.

4.4.4.4.5 The damage evaluation should be recorded in a report presented by the consultant including the repair suggestions of the system and protective operations to prevent future deterioration.

4-4-4-5 Repair of Surface Protective Layers

4.4.4.5.1 Externally applied FRP systems shall be coated with protective surface layer of special material, compatible with the applied system in order to protect the system from exposure and other environmental factors. This layer may deteriorate by time and as a result, the fibers will be exposed. The strength of the system in this case will be affected and the mechanical properties will decrease gradually and the system may be in danger.

4.4.4.5.2 In this case, the missing parts of the protective layer shall be completed, strengthened or totally replaced according to deterioration level. This shall be carried out using materials and recommendations given by the supplier/manufacturer and authorized by the consultant.

4.4.4.5.3 It is preferable to use resins or protective layers for repair of the same type and resource installed in the system to ensure homogeneity unless there is an approval by the consultant to use another material.

4.4.4.5.4 In case of removing the protective layers for total replacement, the FRP system shall be examined to ensure having no defects.

4-4-4-6 Repair Work During Installation

FRP may be exposed to rupture by mistake or due to bad handling. In this case, systems shall be repaired after hardening according to the recommendation of the system manufacturer and after approval by the designer. Some repair methods of FRP systems are given in the following clause.

4-4-4-7 Repair Work for FRP

4.4.4.7.1 Repair of damaged FRP systems are carried out in order to regain its properties and efficiency to resist acting loads and environmental conditions.

4.4.4.7.2 The repair methods vary according to the type of the system and the type of damage.

4.4.4.7.3 It is preferable to use resins or protective layers for repair of the same type and resource as those used in the system to ensure homogeneity between materials unless an approval by the consultant is given to use different materials.

4.4.4.7.4 Repair of small defects is done by bonding a layer or more of FRP on the affected zone with the same thickness, fiber ratio, type of fiber, and fiber orientation as of the original system. Its area should be enough to transmit the loads to other zones. The steps of repair shall be carried out according to the manufacturer instructions.

4.4.4.7.5 Layer separation in small zones could be repaired by injection with epoxy or resin, to regain the continuity and unity of layers.

4.4.4.7.6 Repair of large areas containing defects, delamination or debonding Shall be done by a complete removal of deficient parts. Preparation of the substrate shall be carried out, followed by application of the FRP system according to the recommendations given by the supplier/manufacturer of the system

CHAPTER 5

CONCRETE STRUCTURES REINFORCED WITH FRP BARS

5.1 General Considerations

The main principles for the design of concrete elements reinforced with FRP bars using limit states are presented in this chapter. These limit states ensure sufficient safety level against failure as a result of reaching the ultimate limit state of a cross-section according to section 5.3. The limit states satisfy also all serviceability requirements according to section 5.4, durability and creep rupture endurance requirements according to Chapter 3 of this code. The requirements of this chapter are applicable only to the different types of FRP bars presented in Chapter 2 of this code. This chapter deals only with the design of concrete slabs, beams and slabs on grade reinforced with FRP bars.

5.2 Applications and Use

The brittle behavior of both FRP reinforcement and concrete governs the choice of applications that allow using FRP as reinforcement for concrete members as follows:

5.2.1 Acceptable Applications for FRP Bars

1. As tensile reinforcement for concrete beams and slabs. In these cases, it is acceptable for FRP tension reinforcement to experience compression due to moment reversals or changes in load pattern. The compressive strength of the FRP reinforcement should, however, be neglected.
2. As an alternative to conventional steel reinforcement for concrete members subjected to corrosive environments.
3. As reinforcement for concrete beams and slabs subjected to electro-magnetic fields
4. As shrinkage and temperature reinforcement for different concrete members.
5. As reinforcement for slabs on grade.

5.2.2 Unacceptable Applications for FRP Bars

1. As compression reinforcement in concrete members. Therefore, FRP reinforcement should not be used as reinforcement in columns or other compression members, nor should it be used as compression reinforcement in flexural members such as beams and slabs.
2. As reinforcement for frames due to the brittle failure mode of FRP-reinforced concrete members.

3. As reinforcement for concrete members where moment redistribution is required. Therefore, it is not permitted to reinforce concrete sections subjected to seismic loads with FRP bars.
4. As reinforcement for concrete members subjected to direct shear stresses as dowels.
5. As reinforcement for concrete sections subjected to punching shear stresses.

5.3 Ultimate Strength Limit States

This section presents the general procedures to calculate the ultimate limit capacity of concrete sections subjected to flexural stresses (section 5.3.3), shear stresses (section 5.3.4) as well as the bond strength (section 5.3.6).

5.3.1 Factored Loads

Factored loads should be calculated in accordance with Chapter 3 of the "Egyptian Building Code for the Design and Construction of Reinforced Concrete Structures".

5.3.2 Design Stresses and Strains for FRP Bars

5.3.2.1 The design stresses and strains for FRP bars should be evaluated after satisfying the durability requirements according to Chapter 3 of this code (section 3.5.9). For serviceability limit states, the design material properties should be evaluated without considering the load factors.

5.3.2.2 The design tensile strength of FRP bars at a bend portion can be determined using Eq. (5-1)

$$f^*_{fb} = (0.05\, r_b/d_b + 0.3)\, f^*_{fu} \leq f^*_{fu} \qquad (5\text{-}1)$$

where

f^*_{fb} = design tensile strength of the bend of FRP bar, (N/mm^2);
r_b = radius of the bend, (mm);
d_b = diameter of reinforcing bar, (mm); and
f^*_{fu} = design tensile strength of FRP, considering reductions for service environment according to Chapter 3, (N/mm^2).

5.3.3 Sections Subjected to Bending Moments

This section refers to the design of rectangular sections with a single layer of one type of FRP reinforcement. The concepts described here, however, can also be applied to the analysis and design of members with different geometry and multiple types, multiple layers, or both, of FRP reinforcement.

5.3.3.1 Design Philosophy

Due to the nonductile behavior of both FRP reinforcement and concrete, flexural failure modes of concrete sections reinforced with FRP are brittle in nature. The flexural capacity of an FRP-reinforced flexural member is dependent on whether the failure is governed by concrete crushing in compression or FRP rupture in tension. The brittle failure mode of FRP-reinforced concrete sections is contradicting the recommendations set by the Egyptian Code for the design of concrete sections reinforced with conventional steel bars. These recommendations ensure that the failure is ductile and the steel reinforcement reaches the yield strength prior to crushing of concrete.

If FRP reinforcement ruptures, failure of the member is sudden and brittle. In this case, there would be limited warning of imminent failure in the form of extensive cracking and large deflection due to the significant elongation that FRP reinforcement experiences before rupture. The concrete crushing failure mode is marginally more desirable for flexural members reinforced with FRP bars. By experiencing concrete crushing, a flexural member does exhibit some plastic behavior before failure.

In general, both failure modes (FRP rupture and concrete crushing) are acceptable in governing the design of flexural members reinforced with FRP bars according to the shape of the cross-section. To compensate for the lack of ductility, the member should possess a higher reserve of strength. The suggested margin of safety against failure is therefore higher than that used in traditional steel-reinforced concrete design according to section 5.3.3.5.

5.3.3.2 Fundamental Assumptions

Computations of the strength of cross sections should satisfy the principles of equilibrium and compatibility and should be based on of the following assumptions:

1. Strain in the concrete and the FRP reinforcement is proportional to the distance from the neutral axis (plane section before loading remains plane after loading);
2. The maximum usable compressive strain in the concrete, ε_{cu}, is assumed to be 0.003;
3. The tensile strength of concrete is ignored and FRP reinforcement resists all the tensile stresses;
4. The tensile behavior of the FRP reinforcement is linearly elastic until failure;
5. Perfect bond exists between concrete and FRP reinforcement; and

6. The stress-strain behavior of concrete can be obtained from the measured experimental data or can be idealized as given in section 4.2.1.1.6 of the Egyptian Code for the Design and Construction of Concrete Structures.

5.3.3.3 Flexural Ultimate Limit State

The flexural capacity of an FRP-reinforced flexural member is dependent on whether the failure is governed by concrete crushing or FRP rupture. The failure mode can be determined by comparing the FRP reinforcement ratio to the balanced reinforcement ratio, which can be computed from section 5.3.3.4

5.3.3.4 Balanced Reinforcement Ratio

Balanced reinforcement ratio is the ratio where concrete crushing and FRP rupture occur simultaneously. In this case, the tensile strain in the FRP reinforcement reaches its ultimate value of f^{*}_{fu}/E and the compressive strain in the concrete, ε_{cu}, reaches 0.003. The reinforcement ratio of FRP reinforcement can be computed from Eq. (5-2). The balanced FRP reinforcement ratio can be computed from Eq. (5-3).

$$\mu_f = \frac{A_f}{bd} \tag{5-2}$$

$$\mu_{fb} = 0.8 \frac{0.67 f_{cu}}{f^{*}_{fu}} \quad \frac{\varepsilon_{cu}}{\varepsilon_{cu} + \varepsilon^{*}_{fu}} \tag{5-3}$$

5.3.3.5 Material Strength Reduction Factors

The strength reduction coefficients for concrete and FRP reinforcement can be computed as follows (Figure 5-1)

Tensile Brittle Failure of FRP

$$\begin{aligned} &\mu_f \le \mu_{fb} \\ &\gamma_c = 2.0 \\ &\gamma_f = 2.0 \end{aligned} \tag{5-4}$$

Compression Brittle Failure of Concrete: Transition Zone Between Tensile and Compression Failures

$$\mu_{fb} < \mu_f < 1.4\,\mu_{fb}$$

$$\gamma_c = 2.75 - 0.75 \frac{\mu_f}{\mu_{fb}} \tag{5-5a}$$

$$\gamma_f = 2.75 - 0.75 \frac{\mu_f}{\mu_{fb}} \tag{5-5b}$$

Compression Brittle Failure of Concrete

$$\mu_f \geq 1.4\,\mu_{fb}$$

$$\gamma_c = 1.70\,\mu_f \geq 1.4\,\mu_{fb} \qquad \text{(5-6a)}$$

$$\gamma_f = 1.70 \qquad \text{(5-6-b)}$$

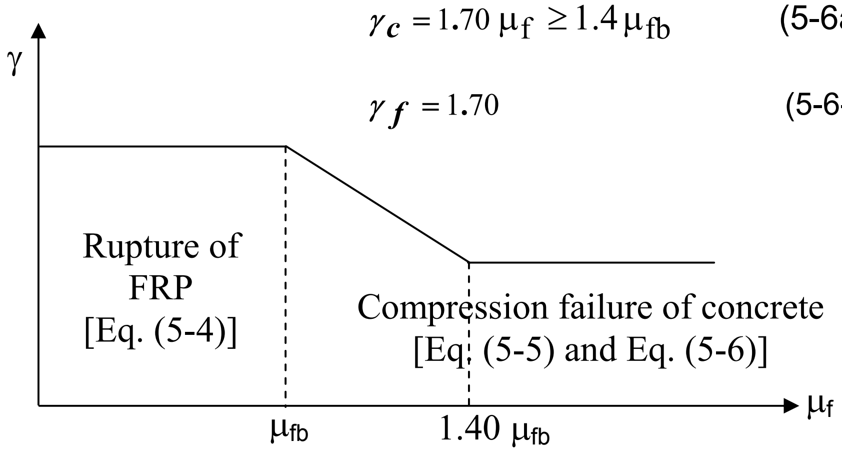


Figure 5-1 Variation of strength reduction coefficients with FRP reinforcement ratio

5.3.3.6 Case I: FRP Reinforcement Ratio is Greater than the Balanced Reinforcement Ratio

When $\mu_f > \mu_{fb}$, the failure of the member is initiated by crushing of the concrete, and the stress distribution in the concrete can be approximated with the equivalent rectangular stress block according to the Egyptian Code for Design and Construction of Concrete Structures (Figure 5-2).

The ultimate limit moment of the cross section can be computed using Eq. (5-7)

$$M_u = \left(\frac{A_f\, f^*_{fe}}{\gamma_f}\right)\left(d - \frac{a}{2}\right) \qquad \text{(5-7)}$$

The depth of the equivalent stress block can be computed from:

$$a = \frac{\dfrac{A_f\, f^*_{fe}}{\gamma_f}}{\left(\dfrac{0.67\, f_{cu}}{\gamma_c}\right) b} \qquad \text{(5-8)}$$

The design stress in the FRP bars, f^*_{fe} can be computed using Eq. (5-9) after considering the environmental reduction factors according to Chapter 3.

$$\frac{f^{*}_{fe}}{\gamma_f} = \left(\frac{0.8d - a}{a}\right) E_f\,\varepsilon_{cu} \tag{5-9}$$

substituting a from Eq. (5-8) into Eq. (5-9) and solving for f^{*}_{fe} gives:

$$\frac{f^{*}_{fe}}{\gamma_f} = \left[\sqrt{\frac{(E_f\varepsilon_{cu})^2}{4} + \frac{0.536 f_{cu}}{\mu_f \gamma_c} E_f\varepsilon_{cu}} - 0.5\,E_f\varepsilon_{cu}\right] \leq \frac{f^{*}_{fu}}{\gamma_f} \tag{5-10}$$

5.3.3.7 Case II: FRP Reinforcement Ratio is smaller than the Balanced Reinforcement Ratio

When $\mu_f < \mu_{fb}$, the failure of the member is initiated by rupture of the FRP bars in tension, and the equivalent rectangular stress block for the concrete is not applicable because the maximum concrete strain (0.003) may not be attained.

In addition, the rectangular stress block factors, α_1 and β_1, are unknown. The factor, α_1, is the ratio of the average concrete stress to the concrete strength. β_1 is the ratio of the depth of the equivalent rectangular stress block to the depth of the neutral axis. The ultimate limit moment in this case can be computed from Eq. (5-11).

$$M_u = \left(\frac{A_f\, f^{*}_{fu}}{\gamma_f}\right)\left(d - \frac{\beta_1 C}{2}\right) \tag{5-11}$$

For a given section, the product of $\beta_1 C$ in Eq. (5-11) varies depending on material properties and FRP reinforcement ratio. The maximum value for this product is equal to $\beta_1 C_b$ and is achieved when the maximum concrete strain (0.003) is attained. A simplified and conservative calculation of the ultimate limit moment of a cross section can be computed from Eq. (5-12).

$$M_u = 0.8\left(\frac{A_f\, f^{*}_{fu}}{\gamma_f}\right)\left(d - \frac{0.8 C_b}{2}\right) \tag{5-12}$$

where

$$C_b = \left(\frac{\varepsilon_{cu}}{\varepsilon_{cu} + \varepsilon^{*}_{fu}}\right) d \tag{5-13}$$

5.3.3.8 Rectangular Sections Subjected to Bending Moments

For rectangular sections, failure should be governed by concrete crushing in the compression zone. To ensure that rupture of FRP bars will not govern the design as result of an increased concrete strength during construction, FRP reinforcement ratio should be greater than $1.4\mu_{fb}$. Design of the section should be performed according to section 5.3.3.6 using the strength reduction coefficients from Eq. (5-6).

5.3.3.9 T- and L-Sections Subjected to Bending Moments with the Flange in Compression

In most cases, failure of T- and L-sections subjected to bending moments with the flange in compression is governed by rupture of FRP bars. Design of these sections can be performed according to section 5.3.3.7 using the strength reduction factors given in Eq. (5-4). Failure can also be governed by crushing of the concrete in compression. In this case, the strength reduction factors shall be computed according to section 5.3.3.5.

5.3.3.10 Minimum Reinforcement Ratio

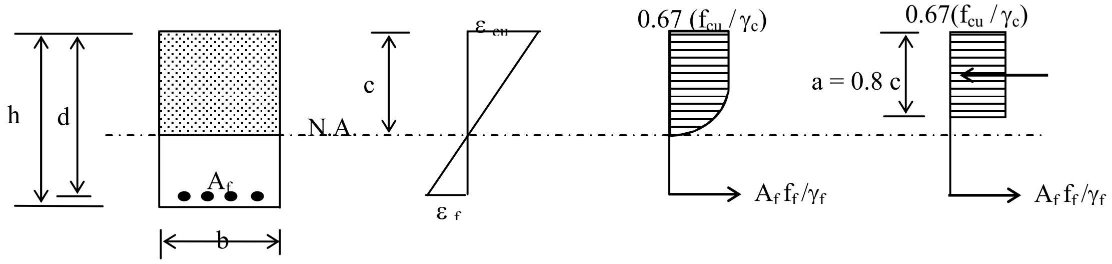
If rupture of FRP bars in tension is the governing mode of failure, a minimum reinforcement ratio shall be provided using Eq. (5-14) to prevent failure upon concrete cracking.

$$\mu_{min} = \frac{A_{f_{min}}}{bd} = \frac{2.5}{f^*_{fu}} \qquad (5\text{-}14)$$

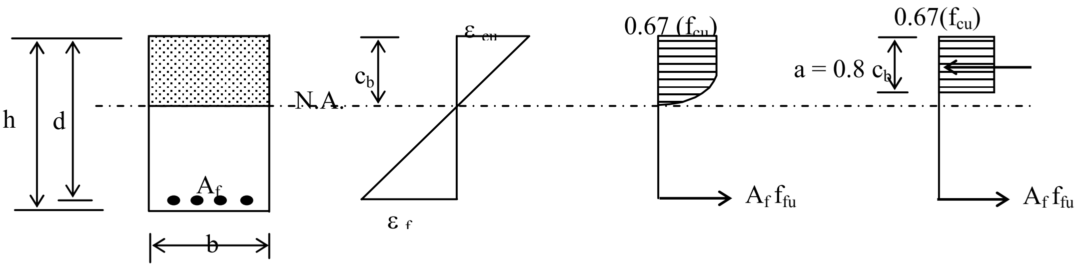
If the failure of the section is governed by concrete crushing in compression, the minimum reinforcement ratio is $1.4\mu_{fb}$

5.3.3.11 Using Multiple Layers or Different Types of FRP Reinforcement in a Concrete Section

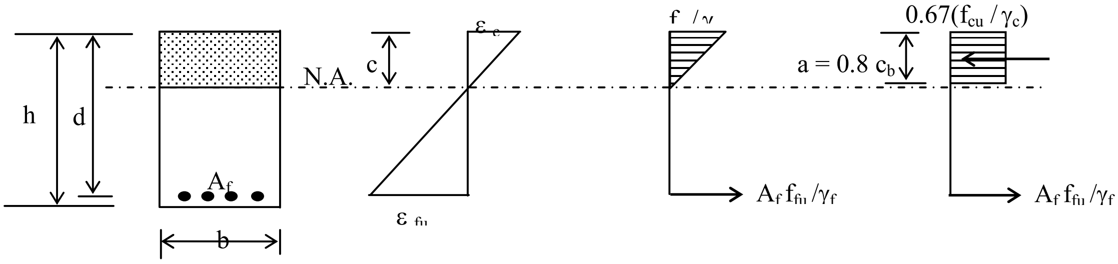
The flexural capacity of a concrete section reinforced with multiple layers of FRP bars shall be computed using the stress level in each reinforcement layer. If different types of FRP bars are used to reinforce a concrete section, the variation in the stress level in each bar type shall be accounted for when calculating the flexural capacity. In these cases, the flexural capacity can be determined based on strain compatibility, internal force equilibrium, and the controlling mode of failure taking into consideration that failure is controlled by rupture of the outermost reinforcement layer.



(a) Failure governed by concrete crushing



(b) Balanced failure condition



(c) Failure governed by FRP rupture (concrete stress may be nonlinear)

Figure 5-2 Stress and strain distribution in FRP-reinforced concrete sections at ultimate

5.3.3.12 Moment Redistribution

It is not permitted to redistribute the bending moments for continuous beams or statically indeterminate structures reinforced with FRP bars.

5.3.3.13 Compression Reinforcement

It is not permitted to use FRP bars as compression reinforcement for flexural members. However, in cases where using FRP bars in the compression region of flexural members can not be avoided, FRP bars shall be carefully confined using stirrups to prevent buckling and minimize the influence of the relatively high transverse expansion of some types of FRP bars.

5.3.4 Ultimate Shear Strength Limit State

5.3.4.1 Concrete Beams Reinforced With FRP Bars

This section presents the procedures for the analysis and design of concrete beams reinforced in flexure and shear with FRP reinforcement. The shear strength of a reinforced concrete cross section is the sum of the shear resistance provided by concrete and the shear reinforcement according to the Egyptian Code for Reinforced Concrete Structures. Several discrepancies exist between this code and the Egyptian Code for Reinforced Concrete Structures regarding the ultimate shear strength limit state requirements. This is attributed to the following different mechanical properties of FRP bars:

1. Relatively low modulus of elasticity;
2. Linear elastic behavior with high tensile strength and no yield point;
3. Lower tensile strength of the bent portion than the straight portion; and
4. Low dowel resistance.

These properties of FRP bars will result in:

1. Smaller neutral axis depth for FRP-reinforced concrete sections compared to steel-reinforced concrete sections.
2. Wider cracks compared to steel-reinforced concrete beams.

As a result of the previous factors, the shear resistance provided by both the aggregate interlock and the compressed concrete is smaller than that of steel-reinforced concrete sections.5.3.4.2 Nominal Ultimate Shear Force in Beams

In general, the maximum shear force in a member occurs at the face of the supports and near concentrated loads. When the support reaction introduces transverse compression in the end region of the member, it is permitted to calculate the shear stresses using the shear force at a distance from the face of the support equal to half of the effective depth of the member. Critical sections for shear design shall be determined according to the Egyptian Code for Design and Construction of Concrete Structures (ECP 203).

5.3.4.2 Nominal Ultimate Shear Force in Beams

In general, the maximum shear force in a member occurs at the face of the supports and near concentrated loads. When the support reaction introduces transverse compression in the end region of the member, it is permitted to calculate the shear stresses using the shear force at a distance from the face of the support equal to half of the effective depth of the member. Critical sections for shear design shall be determined according to the Egyptian Code for Design and Construction of Concrete Structures (ECP 203).

5.3.4.3 Nominal Ultimate Shear Strength

A. For concrete beams and slabs of constant depth, the nominal ultimate shear strength can be computed using Eq. (5-15)

$$q_u = \frac{Q_u}{bd} \qquad (5\text{-}15)$$

where Q_u is the ultimate shear force at the section.

B. Shear failure modes are very brittle in nature and shall be avoided. These modes can be classified into two types:

1. Shear-tension failure, which is controlled by rupture of the FRP shear reinforcement.
2. Shear-compression failure, which is controlled by crushing of the concrete web.

Shear-tension failure is sudden and more brittle in nature compared to shear-compression failure, which is usually accompanied by excessive deflections of the beam. To prevent shear failures, the ultimate shear stress shall not exceed the value given in Eq. (5-16).

$$q_u = 0.70\sqrt{\frac{f_{cu}}{\gamma_c}} \qquad (5\text{-}16)$$

C. The ultimate shear stress for concrete members subjected to shear forces and not accompanied by any torsional moments shall not exceed the larger of 3 N/mm^2 or the value given by Eq. (5-16).

5.3.4.4 Material Strength Reduction Factors

The strength reduction coefficients for both concrete and FRP bars shall be taken as follows:

$$\gamma_c = \gamma_f = 1.50 \qquad (5\text{-}17)$$

5.3.4.5 Nominal Ultimate Concrete Shear Resistance

A. The nominal ultimate concrete shear resistance depends on the axial stiffness of the longitudinal FRP reinforcement (A_f E_f) and can be computed by:

$$q_{cuf} = 0.24\sqrt{\frac{f_{cu}}{\gamma_c}}\left(\frac{\mu_f E_f}{\mu_s E_s}\right) \qquad N/mm^2 \qquad (5\text{-}18)$$

Where,

μ_f = Reinforcement ratio of longitudinal FRP bars

E_f = Modulus of elasticity of FRP bars

μ_s = Maximum reinforcement ratio of longitudinal bars = $5x10^{-4}$ f_{cu}

E_s = Modulus of elasticity of steel bars.

B. For members subjected to axial tension, P_u, the nominal ultimate concrete shear resistance, q_{cuf}, shall be taken equal to zero until more experimental data is available.

5.3.4.6 Nominal Ultimate Shear Resistance of Web Reinforcement in Beams

A. In general, the maximum shear force in a member occurs at the face of the supports and near concentrated loads as shown in Figure 5-3. When the support reaction introduces transverse compression in the end region of the member, it is permitted to calculate the shear stresses using the shear force at a distance from the face of the support equal to half of the effective depth of the member as shown in Figure 5-3.

B. If a concentrated load is acting at a distance, a, less than twice the effective depth of the member ($a<2d$), it is permitted to reduce the resulting shear stresses by multiplying the acting shear force by a/2d.

C. For conditions where the critical section is located at a distance d/2 from the face of the support, the shear force can be assumed constant along all sections located less than d/2 from the face of the support. The critical shear force can be determined using the larger value computed from A and B. If q_u exceeds q_{cuf}, it is essential to use FRP shear reinforcement in one of the following configurations:

1. Stirrups perpendicular to the axis of the member

2. Combination of stirrups inclined by an angle not less than 30 degrees to the axis of the member and stirrups perpendicular to the axis of the member.

The contribution of the shear reinforcement can be computed by:

$$q_{fu} = q_u - 0.5\, q_{cuf} \tag{5-19}$$

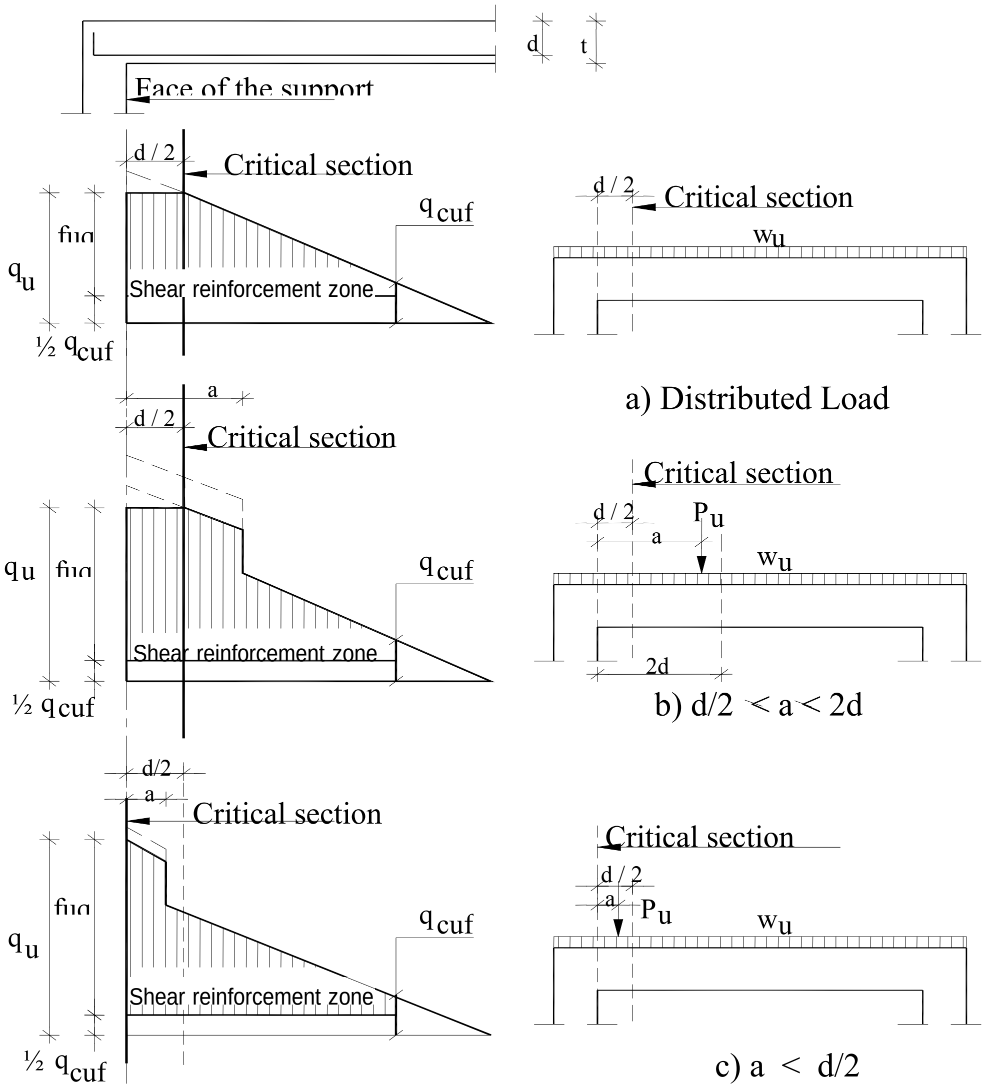


Figure 5-3 Shear stress distribution and location of critical sections

5.3.4.7 Web Reinforcement in Beams

The stress level in the FRP shear reinforcement should be limited to the value given by Eq. (5-20) to avoid rupture of the FRP at the bent portion of the stirrup, limit the crack width and maintain shear integrity of the concrete

$$f_{fq} = 0.002E_f < f^*_{fb} \qquad (5\text{-}20)$$

Where f^*_{fb} is the strength of the bent portion of an FRP stirrup according to Eq. (5-1).

A. When shear reinforcement perpendicular to the axis of the member and no bent bars are used, the amount of FRP shear reinforcement can be computed by

$$\mu_{fq} = \frac{A_{fq}}{bs} = \frac{q_{fu}}{\left(\frac{f_{fq}}{\gamma_f}\right)} \qquad (5\text{-}21)$$

B. When stirrups or bent bars inclined by an angle α with the axis of the member are used as shear reinforcement, the amount of FRP shear reinforcement can be computed by

$$\frac{A_{fqb}}{bs} = \frac{q_{fub}}{\left(\frac{f_{fq}}{\gamma_f}(\sin\alpha + \cos\alpha)\right)} \qquad (5\text{-}22)$$

where

$$q_{fub} = q_{fu} - q_{fus} \qquad (5\text{-}23)$$

q_{fub} = Ultimate shear strength of bent bars

q_{fus} = Ultimate shear strength of stirrups perpendicular to the axis of the member.

5.3.4.8 General Detailing Requirements for Web Reinforcement

A. To prevent brittle shear failure, the minimum shear reinforcement shall not be less than:

$$\mu_{fq_{min}} = \frac{0.4}{f_{fq}} \qquad (5\text{-}24)$$

where f_{fq} is in N/mm^2.

B. The maximum spacing of vertical stirrups along the member shall not exceed d/2 or 200 mm whichever is less. The horizontal spacing between bent bars shall not exceed the effective depth, d.

C. It is permitted to increase the horizontal distance between bent bars to 1.5d provided that the shear stress is less than 1.5 times the concrete shear strength. This distance can be further increased to 2d if the shear stress does not exceed the concrete shear strength.

D. Shear reinforcements are effective only if every single line drawn from the middle height of the member towards the support and inclined by 45 degrees, intercepts at least one stirrup.

E. Construction joints are not recommended at high shear stress zones.

F. The ratio of the internal radius of bend of FRP reinforcement to the diameter of the bar shall not be less than 3.0, ($r_b/d_b \geq 3.0$). FRP stirrups shall be closed with 90 degrees hooks as shown in Figure 5-4.

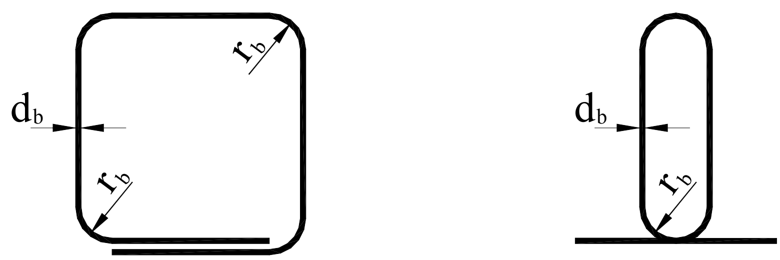


Figure 5-4 Details of FRP stirrups

G. The minimum tail length for FRP stirrups is $12d_b$ ($l_b \geq 12db$) to ensure full bond of hooked FRP bars to concrete as shown in Figure 5-5.

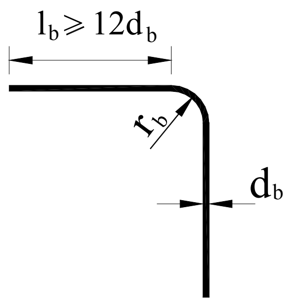


Figure 5-5 Required tail length for FRP stirrups

H. The contribution of shear reinforcement shall be ignored in the design of concrete slabs, voided slabs, embedded beams and beams with total height less than 250 mm or 2.5 times the flange thickness whichever is larger. The design shall be performed considering only the concrete shear strength given in Eq. (5-25)

$$q_{cuf} = 0.16\sqrt{\frac{f_{cu}}{\gamma_c}}\left(\frac{\mu_f E_f}{\mu_s E_s}\right) \quad \text{N/mm}^2 \quad (5\text{-}25)$$

5.3.5 Sections Subjected to Axial Tension or Combined Bending and Axial Tension

A. Design of concrete sections subjected to tensile forces acting inside the cross-section within the distance (d-d′) shall be performed considering only the FRP reinforcement.

B. Design of concrete sections, other than those mentioned in item (A) shall be performed using the principles of equilibrium and strain compatibility.

5.3.6 Development and Splices of FRP Bars

FRP reinforcing bars shall extend on both sides of any section a distance equivalent to the tension force in the bar. The development length of FRP bars needed to prevent splitting and pullout failures is:

$$L_d = \frac{\phi\, \xi\, \eta\, f^*_{fu}}{18.5} \quad (5\text{-}26)$$

The development length shall be provided at critical sections where the maximum tensile stresses in the FRP bars take place and where the bars are either bent or terminated.

where:

ϕ = diameter of the FRP bar.

η = 1.30 for top FRP bars with more than 300 mm of concrete below it

η = 1.00 for all other cases.

ξ = Coefficient depends on the thickness of the concrete cover or the spacing among the longitudinal FRP bars.

ξ = 1.00 if the spacing among longitudinal FRP bars is equal to 2ϕ.

ξ = 1.50 if the spacing among longitudinal FRP bars is equal to ϕ.

5.4 Serviceability Limit States

Concrete members reinforced with FRP bars have a relatively small stiffness after cracking. Therefore, it is quite common that the allowable deflections under service loading conditions can control the design of the member. If the design is controlled by crushing of the concrete in compression, serviceability criteria for deflection and crack width are generally satisfied.

5.4.1 Deflection and Cracking Limit States

In ordinary structures, the maximum deflection of concrete members subjected primarily to bending moments shall not exceed the allowable values given in the Egyptian Code for Concrete Structures.

5.4.1.1 Span-to-Depth Ratio

For all cases and regardless of the span-to-depth ratio of the member, deflections shall be computed and shall not exceed the allowable values according to section 5.4.1.

5.4.1.2 Calculation of Deflection

Short-term deflections can be calculated using one of the common structural analysis techniques. The modulus of elasticity can be taken according to the Egyptian Code for Design and Construction of Concrete Structures.

5.4.1.3 Effective Moment of Inertia, Ie

For calculation of deflections of simply supported members, the effective moment of inertia can be taken as:

$$I_e = \left(\frac{M_{cr}}{M_a}\right)^3 \beta_d \, I_g + \left[1 - \left(\frac{M_{cr}}{M_a}\right)^3\right] I_{cr} \qquad (5\text{-}27)$$

$$\beta_d = 0.5\left[\frac{E_f}{E_s} + 1\right] \qquad (5\text{-}28)$$

where:

I_{cr} = moment of inertia of transformed cracked section, $I_{cr} \leq I_g$

I_g = gross moment of inertia of the section around the neutral axis neglecting the effect of reinforcement and cracking

E_s = modulus of elasticity of steel bars

E_f = modulus of elasticity of FRP bars

M_a = maximum moment in a member at the stage where deflection is computed

M_{cr} = cracking moment and can be taken as:

$$M_{cr} = \frac{f_{ctr}\ I_g}{y_t} \qquad (5\text{-}29)$$

where:

y_t = distance from the neutral axis to the most stressed fibers in tension neglecting the effect of reinforcement and cracking.

f_{ctr} = tensile strength of concrete and can taken as:

$$f_{ctr} = 0.6\sqrt{f_{cu}} \qquad (5\text{-}30)$$

5.4.1.4 For continuous members, the effective moment of inertia can be taken as the average of both values computed at the sections subjected to maximum positive and maximum negative bending moments.

5.4.1.5 Creep due to the presence of sustained loads introduces additional deflections that increase with time. The additional deflection due to creep can be considered by multiplying the initial deflections due to sustained loads by the factor α, which can be taken as 1.2.

5.4.2 Cracking Limit State

Due to the excellent corrosion-resistance characteristics of FRP bars, the crack width limitation can be relaxed for FRP-reinforced concrete members. The maximum allowable crack width for concrete structures reinforced with FRP bars shall not exceed 0.50 mm to ensure the structural integrity and durability of concrete.

5.5 Slabs on Grade

FRP bars can be used as shrinkage and temperature reinforcement to control cracking in slabs on grade. The bars are usually placed in the upper half of the slab and are used primarily to control the crack width, distribution and spacing. Therefore, a wider spacing between joints can be permitted. The amount of FRP reinforcement can be computed from:

$$A_{f,sh} = \frac{5000\ \mu\ L\ \gamma_{RC}\ t}{0.0012\ E_f} \quad (5\text{-}31)$$

where:

$A_{f,sh}$ = area of shrinkage and temperature FRP reinforcement per linear meter, (mm^2/m)

μ = coefficient of subgrade friction and can be taken equal to 1.5

L = distance between joints in a slab on grade (mm)

E_f = modulus of elasticity of FRP bars (N/mm^2)

γ_{RC} = unit weight of the concrete for the slab on grade (N/mm^3)

t = thickness of the slab on grade (mm).

APPENDIX I- NOTATION

a	=	Equivalent compression block depth
A_f	=	Cross section area of FRP external reinforcement
A_c	=	Concrete cross section area
A_{sc}	=	Area of longitudinal reinforcement in column
$A_{f,sh}$	=	Area of bars per unit length
b_w	=	Width of concrete section subjected to tension
b_{FRP}	=	Effective width of FRP
b_f	=	Width of FRP laminates
b	=	Small dimension of column section
b_w	=	Width of concrete section
C_E	=	Environmental-reduction factor
C1	=	Creep limitation
d	=	Effective depth of concrete section
d_f	=	Depth of FRP
d_b	=	Bar diameter
D	=	Diameter of circular column
DL	=	Dead loads
E_f	=	Modulus of elasticity of FRP
E_m	=	Modulus of elasticity of polymer
I_{cr}	=	Moment of inertia of cracked section transformed to concrete
I_g	=	Moment of inertia of gross section with respect to neutral axis not considering cracking
LL	=	Live loads
k1	=	Modification factor applied to account the concrete strength
k2	=	Modification factor applied to account wrapping scheme
N	=	Number of plies of FRP reinforcement
t	=	Long dimension of column section
t_f	=	Nominal thickness of one ply of the FRP reinforcement
f_{fb}	=	Ultimate design strength of FRP bars at rotaion
f_{fe}	=	Effective stress in the FRP; stress level attained at section failure.
f_{fq}	=	Ultimate tensile stress allowable for longitudinal bar reinforcement
f_{ss}	=	Stress level in steel reinforcement at service loads
f_{fu}	=	Design ultimate tensile strength of FRP

f_f = Stress level in the FRP reinforcement
f_{cu} = Characteristic compressive stress of concrete
f_{cuc} = Characteristic compressive stress of confined concrete
f_{ctr} = Crack stress for concrete subjected to tension
f_m = Resin strength
f_y = Yield stress of steel reinforcement
f_l = Confining pressure due to FRP jacket
$f_{f,s}$ = Stress level in the FRP caused by a moment withen the elastic range of the member
L = Spacing between shrinkage joints
L_{ed} = Required bond length of FRP laminate
L_{df} = Development length of FRP system
L_e = Active bond length of FRP laminate
K_v = coefficient reduction factor for bond stress
K_e = Coefficient depends on the efficiency of partial wrapping of circular columns
M_a = Maximum bending moment when calculating deflection
M_{cr} = Cracking moment
M_u = Factored moment at section
P_u = Nominal axial load strength at given eccentricity
P_m = Total width of laminates used to increase the tensile strength
q_u = Factored shear force
q_{su} = shear strength of shear reinforcement
q_{cu} = shear strength of concrete section
q_{fu} = shear strength of FRP
r_b = Radius of circulation
S_f = Spacing between FRP laminates axes
T_f = Additional tensile strength due to using FRP
U = Ultimate load
V_f = Fiber volume fraction
V_m = Matrix volume fraction
w_f = Width of FRP laminate
y_t = Distance from neutral axis to the extreme tension fiber, not considering cracking and steel reinforcement
Z = Depth of neutral axis at service loads
α = Angle of inclination between FRP and element axis
γ_f = FRP reduction factor
γ_c = Concrete reduction factor
γ_s = Steel reduction factor

ε_{bi}	=	Strain level in the concrete substrate at the time of the FRP installation
ε_{cu}	=	Maximum usable compressive strain of concrete
ε^{*}_{fu}	=	Ultimate rupture strain of the FRP considering environmental effects
ε_{fe}	=	Allowable strain in FRP laminate
ε_{fu}	=	Design rupture strain of FRP reinforcement
k_m	=	Coefficient depends on the bond between concrete and FRP
ε_s	=	Strain level in the steel reinforcement
ε_{sy}	=	Yield strain of steel reinforcement
ε_{ef}	=	Effective strain level in FRP reinforcement
μ_f	=	Ratio of FRP reinforcement in case of partial wrapping
μ_s	=	Ratio of longitudinal reinforcement of column cross section
μ_{fb}	=	Balanced reinforcement ratio
μ	=	Soil friction coefficient

APPENDIX II

EGYPTIAN STANDING CODE COMMITTEE FOR THE USE OF FIBER REINFORCED POLYMER (FRP) IN THE CONSTRUCTION FIELDS

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DURABILITY OF FIBER REINFORCED POLYMERS (FRP) COMMITTEE
REPAIR AND STRENGTHENING OF REINFORCED CONCRETE STRUCTURES USING FIBER REINFORCED POLYMER, (FRP) COMMITTEE
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