The Islamic University–Gaza

Research and Postgraduate Affairs

Faculty of Engineering

Master of Civil Engineering

الجامعـــــــة الإسـلاميـة– غـزة

شئون البحث العلمي والدراسات العليا

كـليـــــــــــة الهنـــــــدســـــة

ماجستيـــر هندســـة مدنيـــــة

Finite Element Modeling Of Reinforced Concrete Columns Strengthened Externally With CFRP Sheets

نمذجة الاعمدة الخرسانية المقواة من الخارج بألواح الفايبر الكربونية باستخدام العناصر المحددة

Ahmed Jehad Ayyad

Supervised by

Dr. Mohammed Arafa
Associate prof. of Civil Engineering

Dr. Mamoun Alqedra
Associate prof. of Civil Engineering

A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in Civil Engineering

October /2016

إقـــــرار

أنا الموقع أدناه مقدم الرسالة التي تحمل العنوان:

Finite Element Modeling Of Reinforced Concrete Columns Strengthened Externally With CFRP Sheets

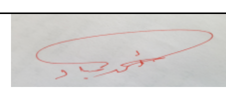
نمذجة الاعمدة الخرسانية المقواة من الخارج بألواح الفايبر الكربونية باستخدام العناصر المحددة

أقر بأن ما اشتملت عليه هذه الرسالة إنما هو نتاج جهدي الخاص، باستثناء ما تمت الإشارة إليه حيثما ورد، وأن هذه الرسالة ككل أو أي جزء منها لم يقدم من قبل الاخرين لنيل درجة أو لقب علمي أو بحثي لدى أي مؤسسة تعليمية أو بحثية أخرى.

Declaration

I understand the nature of plagiarism, and I am aware of the University's policy on this.

The work provided in this thesis, unless otherwise referenced, is the researcher's own work, and has not been submitted by others elsewhere for any other degree or qualification.

Student's name:	احمد جهاد عياد	اسم الطالب:
Signature:		التوقيع:
Date:	16/10/2016	التاريخ:

بســم الله الرحمن الرحيم

الجامعة الإسلامية-غزة
The Islamic University of Gaza

مكتب نائب الرئيس للبحث العلمي والدراسات العليا   هاتف داخلي 1150

الرقم: ج س غ/35/ Ref:

التاريخ: 2016/12/07 Date:

نتيجة الحكم على أطروحة ماجستير

بناءً على موافقة شئون البحث العلمي والدراسات العليا بالجامعة الإسلامية بغزة على تشكيل لجنة الحكم على أطروحة الباحث/ **أحمد جهاد على عياد** لنيل درجة الماجستير في **كلية *الهندسة*** قسم الهندسة المدنية – تصميم وتأهيل المنشآت وموضوعها:

نمذجة الاعمدة الخرسانية المقواة من الخارج بألواح الفايبر الكربونية باستخدام العناصر المحددة

Finite Element model of Reinforced Concrete Columns Strengthened Externally With CFRP Sheets

وبعد المناقشة التي تمت اليوم الأربعاء 08 ربيع الأول 1438هـ، الموافق 2016/12/07م الساعة الواحدة ظهراً، اجتمعت لجنة الحكم على الأطروحة والمكونة من:

د. محمد حسني عرفة	مشرفاً ورئيساً	....
د. مأمون عبد الحميد القدرة	مشرفا	....
أ.د. سمير محمد شحادة	مناقشاً داخلياً	....
د. علي ابراهيم تايه	مناقشاً خارجياً	8.1.2017 ....

وبعد المداولة أوصت اللجنة بمنح الباحث درجة الماجستير في **كلية *الهندسة*** / قسم الهندسة المدنية- تصميم وتأهيل المنشآت.

واللجنة إذ تمنحه هذه الدرجة فإنها توصيه بتقوى الله ولزوم طاعته وأن يسخر علمه في خدمة دينه ووطنه.

والله ولي التوفيق ،،،

نائب الرئيس لشئون البحث العلمي والدراسات العليا

أ.د. عبدالرؤوف علي المناعمة

+97082644400 +97082644800 public@iugaza.edu.ps www.iugaza.edu.ps iugaza iugaza mediaiug iugaza
P.O Box 108, Rimal,Gaza,Palestine ص.ب 108 الرمال . غزة . فلسطين

Abstract

Rehabilitation of old buildings is more economical than rebuilding them. That`s why the behavior of strengthening techniques should be understood to make the best decision for rehabilitation in order to save time and cost. The behavior of reinforced concrete column strengthened externally with carbon fiber reinforced Polymers (CFRP) is highly affected by the way in which these composites are applied to the column.

This study presents a simple finite element model (FE) able to estimate the load-carrying capacity and ductility of reinforced concrete (RC) square columns strengthened with externally bonded fiber reinforced polymer (FRP) plates / sheets.

The finite element model of reinforced concrete columns was developed for columns externally strengthened with carbon fiber reinforced polymers (CFRP) using the commercial Finite Element Modeling software ANSYS, in order to investigate the behavior of these columns.

The column which size was 250×250×500 mm is modeled and analyzed using a non-linear finite element method. Two parameters of wrap thickness and fiber orientation were considered. The finite element analysis results were in good agreement with experimental data presented by other researchers.

The analysis results demonstrated significant enhancement in the compressive strength and ductility of the FRP-wrapped rectangular RC columns compared to unstrengthened RC columns. It was observed that the behavior of the columns was greatly affected by the analysis parameters. The gain in axial compressive strength was observed to be the highest in the columns wrapped with the hoop orientation; but the highest axial strain and ductility were observed in the columns wrapped with the fiber orientation of ±45° with respect to the horizontal.

الملخص

إعادة تأهيل المباني القديمة هو أكثر اقتصادا من إعادة بناءها لهذا السبب ينبغي فهم طرق دعم الأبنية لاتخاذ أفضل قرار لإعادة تأهل تلك المباني و ذلك لتوفير الوقت و التكلفة .

إن سلوك الأعمدة الخراسانية المدعمة من الخارج ألواح الفايبر الكربونية تتأثر بصورة كبيرة بالط ريقة التي يتم فيها وضع ألواح الفايبر .

و هذه الدراسة لنموذج بسيط بطريقة العناصر المحددة لتحديد قوة تحمل و مرونة الأعمدة الخرسانية المربعة المدعمة من الخارج بألواح الفايبر الكربونية .

و تم تطوير نموذج الأعمدة الخرسانية المدعم بألواح الفايبر الكربونية باستخدام برنامج ANSYS الإصدار 14 ، ذلك من اجل دراسة سلوك تلك الأعمدة .

أبعاد العمود الخرساني المستخدم في نموذج العناصر المحددة هي 250×250×500 مليمتر ز و قد اخذ بعين الاعتبار المعياران سماكة و اتجاه ألواح الفايبر الكربونية .

وقد جاء هذا التحليل متوافقا مع البيانات المقدمة من الباحثين . وقد أوضحت نتائج تحليل النموذج دعم كبير في قوة التحمل و مرونة الأعمدة المدعمة بالفايبر مقارنة بالأعمدة الغير مدعمة .

وقد كان من الملحوظ إن سلوك تلك الأعمدة يتأثر بشكل واضح بمعايير التحليل ، كما أن قوة تحمل الأعمدة المغطاة بألواح الفايبر بطريقة دائرية تكون الأكثر بينما تزداد المرونة أكثر في الأعمدة المغطاة بالألواح بزاوية التفاف °45 .

Dedication

To my father

To my mother

To my sisters

To my wife ,

To my friends,

For their endless support

Acknowledgments

I thank almighty Allah for giving me patience, strength, and determination to accomplish this work.

I also would like to express my sincere appreciation to my supervisors, Dr. Mohammed Arafa and Dr. Mamoun AlQedra for their guidance and strong support throughout the duration of this thesis.

Deep thanks and gratitude are due to my father, **Mr. Jehad Ayyad** and my mother **Asmaa abu baker** for their infinite support and encouragement.

I would like to express my thanks to my wife **Dr.Israa batta** for her patience and support during the time in which this work was done.

I also thank my sisters **Huda** , **Hadeel** and **Tamam**, and my friends for their encouragement.

List of Contents

List Of Tables

List Of Figures

List Of Symbols And Abbreviation

f_c'	Concrete compressive strength.
E_c	Modulus elasticity of concrete.
f_c	Uniaxial crushing strength of concrete.
f_t	Ultimate uniaxial tensile strength of concrete.
f_{cb}	Ultimate biaxial compressive strength of concrete.
f_1	Ultimate compressive strength of concrete for a state of biaxial compression superimposed on hydrostatic stress state σ_h^a.
f_2	Ultimate compressive strength of concrete for a state of uniaxial compression superimposed on hydrostatic stress state.
E_s	Modulus elasticity of steel.
f_y	Yield strength of steel.
ε_y	The strain at which steel yields.
f_u	Peak strength of steel.
ε_u	The strain at which peak strength of steel is achieved.
f_s	The strain at which steel facture occurs.
ε_{max}	The strain at which fracture of steel occurs.
f_s	The stress at which steel facture occurs.
ν	Poisson's ratio.
E_X	Modulus of elasticity in x-direction.
FRP	Fiber-reinforced polymer.
RC	Rinforced concrete
CFRP	Carbon Fiber-Reinforced Polymers
μ	Ductility ratios

Chapter 1
Introduction

Chapter1
Introduction

1.1 Background

The strengthening of reinforced concrete (RC) structures using advanced fiber-reinforced polymer (FRP), and in particular the behavior of FRP-strengthened RC structures is a topic which has become very popular in recent years. This popularity has arisen due to the need to maintain and upgrade essential infrastructure in all parts of the world, combined with the well-known advantages of FRP, such as good corrosion resistance and ease for site handling due to their light weight. The continuous reduction in the material cost of FRP composites has also contributed to their popularity. Reinforced concrete (RC) Columns with carbon fiber-reinforced polymer CFRP composites offer an attractive solution to enhance the strengthening of columns. (Teng, Chen, Smith, & Lam, 2001)

While experimental methods of investigation are extremely useful in obtaining information about the composite behavior of FRP and reinforced concrete, the use of numerical models helps in developing a good understanding of the behavior at lower costs .

In this research, a three dimensional non-linear finite element analysis model for strengthening of reinforced concrete columns with carbon fiber reinforced polymers (CFRP) will be presented. The model will make use of the commercial Finite Element modeling software ANSYS to study the effects of different parameters that are important in the response of the strengthened columns.

1.2 Problem statement

Rehabilitation of old building is more economical than rebuilding them . That`s why the behavior of strengthening techniques should be understood to make the best decision for rehabilitation and helpful to save time and cost.

The behavior of reinforced concrete column strengthened externally with CFRP is highly affected by the way in which these composites are applied to the column. In this research, a nonlinear finite element model of RC column strengthened with CFRP will be investigated in order to achieve the best utilization of this strengthening technique in terms of load bearing capacity and possible failure modes.

1.3 Aim and objectives

The aim of this research is to develop a 3D non linear finite element model of reinforced concrete columns externally strengthened with CFRP using the commercial Finite Element Modeling software ANSYS, in order to investigate behavior of these columns. The following objectives are set to achieve the aim of the study:

1. Identify the suitable consecutive element types available in ANSYS library that are capable of modeling the behavior of RC columns externally strengthened with CFRP. (Concrete, steel reinforcement bars, interface between concrete and steel, loading plates, CFRP, and interface between concrete and CFRP).
2. Develop three dimensional finite element model to simulate the behavior of reinforced concrete columns externally strengthened with CFRP.
3. Conduct a validation and a verification process of the model by comparing results obtained from the model with observations obtained from experimental columns tests available in the literature.
4. Conduct a parametric study using ANSYS to evaluate the effect of different parameters on the behavior of strengthened columns.

1.4 Methodology

To complete this work the following steps were conducted:

<u>Step 1:</u> Review for available literature for the finite element modeling and experimental works related to strengthening of reinforced concrete column with Carbon Fiber-Reinforced polymers (CFRP) will be conducted.

<u>Step 2:</u> A non-linear three dimensional finite element model will be developed to simulate the behavior of reinforced concrete columns externally strengthened with Carbon Fiber-Reinforced Polymers (CFRP), using the commercial finite element modeling software ANSYS

<u>Step 3:</u> Analysis of the model.

<u>Step 4:</u> Draw conclusions and suggest recommendations.

1.5 Layout of the thesis

This thesis consists of six chapters, which are arranged in a logical sequence for the reader to follow. Chapter 1: discusses The plan of this thesis Chapter 2 a background about Fiber Reinforced Polymers FRP and concrete and reinforcement . Chapter 3 Mechanical Behavior and Finite Element Modeling of Materials. Chapter 4 Building of ANSYS Finite Element Models, Chapter 5: Verification of ANSYS Finite Element Models and Parametric Study, and Chapter 6: Conclusions and Recommendations .

Chapter 2
Literature Review

Chapter 2
Literature Review

2.1 Introduction

In this chapter, a background about Fiber Reinforced Polymers FRP (constituents, advantages, disadvantages, types) is presented. Typical applications of CFRP for external strengthening of RC columns, installation techniques of CFRP in strengthening applications, and finally, literature works about FE analysis of RC columns strengthened with CFRP using ANSYS are be presented.

2.2 Constituents of Fiber Reinforced Polymers

Fiber-reinforced polymer(FRP), also Fiber-reinforced plastic, is a composite material made of a polymer matrix reinforced with fibers. The fibers are usually glass, carbon, or aramid, although other fibers such as paper or wood or asbestos have been sometimes used. The polymer is usually an epoxy, vinylester or polyester thermosetting plastic, and phenol formaldehyde resins are still in use. FRPs are commonly used in the aerospace, automotive, marine, and construction industries. Composite materials are engineered or naturally occurring materials made from two or more constituent materials with significantly different physical or chemical properties which remain separate and distinct within the finished structure. Most composites have strong, stiff fibers in a matrix which is weaker and less stiff. The objective is usually to make a component which is strong and stiff, often with a low density. Commercial material commonly has glass or carbon fibers in matrices based on thermosetting polymers, such as epoxy or polyester resins. Sometimes, thermoplastic polymers may be preferred, since they are moldable after initial production. There are further classes of composite in which the matrix is a metal or a ceramic. For the most part, these are still in a developmental stage, with problems of high manufacturing costs yet to be overcome. Furthermore, in these composites the reasons for adding the fibers (or, in some cases, particles) are often rather complex; for example, improvements may be sought in creep, wear, fracture toughness, thermal stability, etc (Martin, 2013).

2.3 Advantages and Disadvantages of Fiber Reinforced Polymers

FRP materials for use in concrete strengthening applications have a number of key advantages

over conventional reinforcing steel. Some of the most important advantages include (CSC.TR-N55, 2000) :

1. Do not corrode electrochemically, and have demonstrated excellent durability in a number of harsh environmental condition.
2. Have extremely high strength-to weight ratios (typically weigh less than one fifth the weight of steel, with tensile strengths that can be as much as 8 to 10 times as high).
3. Their installation is easy and simple with no need for temporary support.
4. Have low thermal conductivity.

FRP materials also have a number of potential disadvantages (ACI 440R-07., 2007):

1. The relatively high cost of the materials.
2. The risk of fire, vandalism or accidental damage, unless the strengthening is protected.
3. The relatively low elastic modulus of FRPs as compared with steel.

2.4 Types of FRP Materials Used in Construction Applications

The type of fibers used as the reinforcement is the basics for classification of FRP composites. There are three types of fibers dominating civil engineering industry: glass, carbon and aramid fibers.

2.4.1 Glass fibers

Glass fibers are a processed form of glass, which is composed of a number of oxides (mostly silica oxide), together with other raw materials (such as limestone, fluorspar, boric acid, clay). They are manufactured by drawing those melted oxides into filaments ranging from 3 Mm to 24 Mm ,Figure (2.1) shows the glass fiber fabric. There are five forms of glass fibers used as the reinforcement of the matrix material: chopped fibers, chopped strands, chopped strand mats, woven fabrics, and surface tissue. The glass fiber strands and woven fabrics are the forms most commonly used in civil engineering application. Relatively low cost comparing to other kinds of fibers makes E-glass fibers the most commonly used fibers available in the construction industry. The disadvantages of glass fibers are a relatively low Young´s modulus, the low humidity and alkaline resistance as well as low long term strength due to stress rupture. For applications involving concrete a more alkaline resistant so-called AR fiber (also called CemFil fiber) has been developed with increased zircon oxide content (Potyrała, 2011)

Figure (2.1) Glass fiber fabric Carbon fibers

Carbon fibers are a type of high-performance fiber available for civil engineering application. They are manufactured by controlled pyrolysis and crystallization of organic precursors at temperatures above 2000°C. In this process, carbon crystallites are produced and orientated along the fiber length, Figure(2.2) shows carbon fiber fabric. There are three choices of precursor used in manufacturing process of carbon fibers - rayon precursors, polyacrylonitrile (PAN) precursors, and pitch precursor. PAN precursors are the major precursors for commercial carbon fibers. It yields about 50% of original fiber mass. Pitch precursors also have high carbon yield at lower cost.

Carbon fibers have high elastic modulus and fatigue strength than those of glass fibers. Considering service life, studies suggests that carbon fiber reinforced polymers have more potential than aramid and glass fibers. Their disadvantages include inherent anisotropy (reduced radial strength), comparatively high energy requirements in their production as well as relatively high costs (Potyrała, 2011)

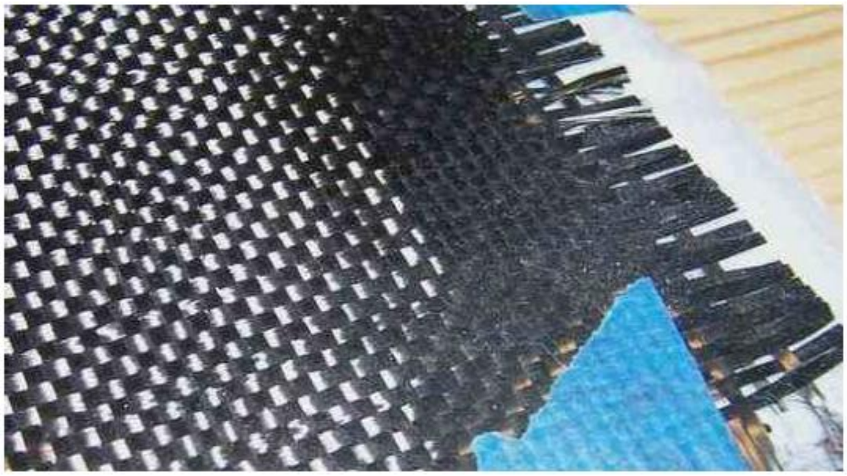


Figure (2.2):Carbon fiber fabric

2.4.2 Aramid fibers

Aramid or aromatic polyamide fiber is one of the two high-performance fibers used in civil engineering application. It is manufactured by extruding a solution of aromatic polyamide at a temperature between -50°C and -80°C into a hot cylinder at 200°C. Fibers left from evaporation are then stretched and drawn to increase their strength and stiffness. During this process, aramid molecules become highly oriented in the longitudinal direction , Figure(2.3) shows Single aramid fiber and aramid fiber fabric . Aramid fibers have high static, dynamic fatigue, and impact strengths. The disadvantages are: low compressive strength (500-1000 MPa), reduced long-term strength (stress rupture) as well as sensitivity to UV radiation. Another drawback of aramid fibers is that they are difficult for cutting and machining (Potyrała, 2011)

2.5 FRP Applications for External Strengthening of RC Columns

2.5.1 Axial Compression

Strength enhancement can be achieved by using steel confinement as well as FRP confinement. However FRP-strengthened concrete behaves differently from steel- strengthened concrete.

Therefore already established design guidelines for steel strengthened concrete columns cannot be applied for FRP strengthened columns. As shown in Figure(2.4), the confinement actions provided by steel and FRP wrapping are different. This behavior is due to the linear behavior (without any yield points) of carbon fiber composites. After the initial linearly elastic phase, steel displays a yielding plateau. Therefore after reaching the maximum stress corresponding to yielding, the confining pressure remains constant. In the contrary, FRP wrapping continues to provide continuously increasing confining pressure until it fails (elastic behavior).In designing the FRP strengthening system for columns, it is necessary to estimate the strength enhancement of concrete due to FRP composite confinement. This confining action depends on the strain in FRP composite which is same as the lateral strain of concrete (lateral dilation).

Therefore the passive confining pressure provided by the externally bonded FRP composites depends on the lateral dilation of concrete. Therefore constitutive model for concrete which can predict the lateral dilation of concrete is ideal in estimating the passive confining pressure provided by the FR The maximum confining pressure provided by FRP composites is related to the amount and strength of FRP and the diameter of the strengthened concrete core. However, the ultimate strength of the strengthened concrete is closely related to the failure strain of the FRP wrapping reinforcement.

As the FRP is subjected to tension in hoop direction, eventual failure occurs when its hoop tensile strength is reached. Many researchers have noted that the strain measured in the confining FRP at rupture is in many cases lower than the ultimate strain of FRP tested for tensile strength. The recorded hoop strains corresponding to rupture had a range of 50 to 80% of the failure strain obtained in the tensile tests This reduction is due to the following reasons:

- The triaxial state of stress of the wrapping reinforcement.The quality of the execution
- If the surface preparation for FRP application is not good enough, some part of the circumferential strain is used to stretch the fibers. Moreover, fibers may be damaged at improperly rounded edges or local protrusionThe curve shape of the wrapping reinforcement
- Size effects when applying multiple layers

Figure (2-5) shows the concept of composite action, where the FRP jacket provides longitudinal load carrying capacity as well as lateral confinement (it undergoes both longitudinal and lateral strains). This behavior depends on the fiber arrangement and bond interface characteristics. The ultimate stress and strain are reduced with a possibility of micro-buckling and de-lamination. Therefore failure of the member occurs at a lower circumferential strain than in case of no composite action. In case of no composite action, the FRP jacket is subjected to lateral strain only and fails due to either fiber collapse or de- lamination between plies. This failure takes place at a circumferential strain lower than the ultimate strain. Depending on the loading condition (axial loading, shear and bending) the load- carrying capacity of the column should be calculated according to appropriate confinement models. (Setunge, 2002)

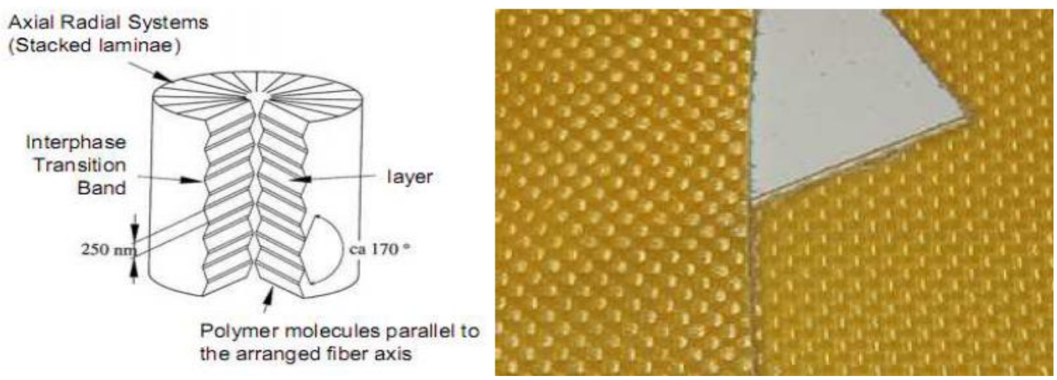


Figure (2.3): Single aramid fiber and ramid fiber fabric

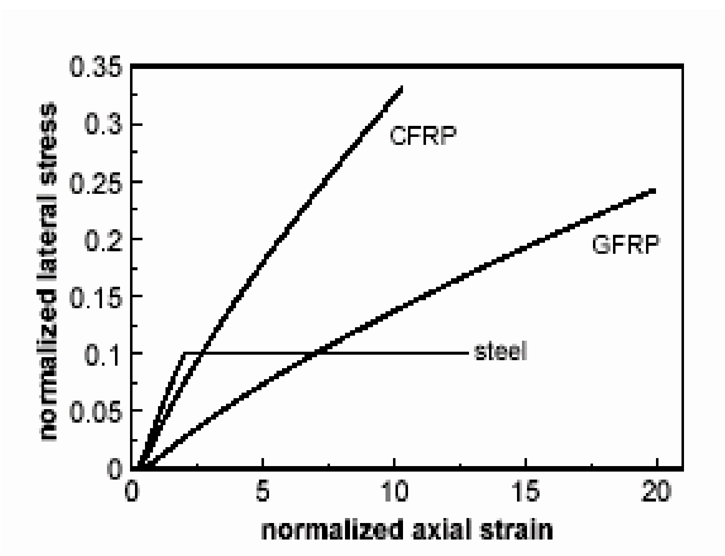


Figure (2.4): the difference confinement actions provided by steel and FRP wrapping

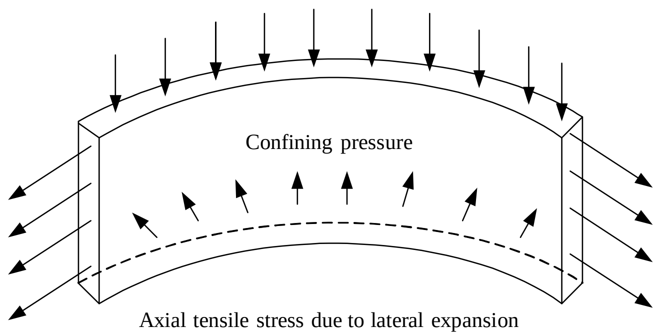


Figure (2.5): Triaxial state of stress in FRP jackets

2.5.2 Tensile Strengthening

FRP composites can be used to provide additional tensile strength to concrete members. It depends on the design tensile strength of FRP and the ability to transfer stress into the substrate . The tensile strength contribution of FRP can be directly calculated using Hooke's law because of its linear-elastic behavior. (Setunge, 2002)

2.5.3 Ductility

The collapse of and severe damage to many buildings and bridges in recent earthquakes have highlighted the need for the seismic retrofit of seismically inefficient structures. Most of the structural failures during recent earthquakes were attributed to poor column behavior.

Figure (2.6) shows three photos of column failures during Kobe 1995 earthquake. These failures are due to inadequacy of confining reinforcement and bad detailing, which resulted in improper confinement. In concrete structures, the ability to withstand strong earthquakes depends mainly on the formation of plastic hinges and their capability of energy absorption and dissipation without a major loss of strength capacity.

Within the plastic hinge, all the inelastic deformations are assumed to occur. The region outside the hinge is assumed to remain elastic at all times. It is preferable to design structures with strong columns and weak beams with plastic hinges forming in the beams and not in columns. However, it may not always be possible to design structures Using steel reinforcement is the traditional method of increasing ductility. Recent advances in FRP technology have proven that

FRP composites can be used to increase the ductility of like this, and hinges may develop in columns.

Figure (2.6): Column failures in Kobe 1995 earthquake

concrete columns. Methods of improving ductility using FRP composites are described here in brief .The purpose of seismic retrofit of RC columns is to achieve a sufficient level of deformation ductility to dissipate seismic energy before one of the failure modes becomes critical. The displacement ductility factor or the curvature ductility factor has been commonly used to quantify the ductility of the seismic performance of a structure. In order to achieve a target displacement ductility factor, $\mu\Delta$, it is possible to find the thickness of the FRP jacket. The method is explained in FIB Bulletin 14, 2001 and is as follows.

Equivalent plastic hinge length Lp for a given column is calculated based on the yield stress and diameter of longitudinal rebars.

2.6 Strengthening Techniques using FRP

The strengthening techniques are concerned with the application of FRP as structural reinforcement bonded to an existing concrete substrate structure. The technique can be used under different conditions and at different locations of the structural member taking into account all specifications and requirements.

2.6.1 Basic technique

The most widely used FRP strengthening technique is the manual application of wet lay-up (hand lay-up) or prefabricated systems using cold cured adhesive bonding. The main and the important feature of this technique is that the fibers of externally bonded FRP composites are in parallel as practicable with the direction of principal tensile stresses. Typical applications of the hand lay-up and prefabricated systems are illustrated in Figure(2.7).

The basic technique of FRP strengthening described here refers to the manual application of FRP reinforcement to an existing member. A two-part cold cured bonding agent (normally epoxy-based) is used to achieve bonding. The basic technique involves three acting elements Substrate and Adhesive/Resin and FRP reinforcement

FRP composite is bonded to an existing structure to enhance its strength. The material type of that structure is the substrate. The behavior of the thus strengthened structure heavily depends on a good concrete substrate and the preparation of the concrete surface. the initial conditions of the concrete surface in terms of strength, carbonation, unevenness, imperfections,cracks, type and possible corrosion of internal steel reinforcement, humidity, level of chloride and sulphate ions, etc. should be known.

reinforcement. It may have to impregnate "wet lay-up" types of FRP system depending on the type of FRP reinforcement.

For example in MBrace FRP strengthening systems, they use cold curing epoxy resin systems. MBT-MBrace Resicem is a newly developed cementitious epoxy matrix FRP reinforcement

Depending on the application of the FRP composites, they can be categorized as follows:

(a) (b)

Figure (2.7): (a) Hand lay-up CFRP sheets. (b) Application of prefabricated strips

2.6.1.1 Prefab or pre-cured strips or laminates

These FRP strips are provided as fully cured composites, which have their final shape, strength and stiffness. They are mostly available as thin strips or laminates (thickness about 1.0 to 1.5 mm), similar to steel plates. For this type of strip the adhesive provides the bond between the strip and the concrete only.

2.6.1.2 Wet lay-up (hand lay-up) or cured in situ sheets or fabrics

These FRP materials are available as "dry fiber", which means that no resin is inside the FRP before applying, or "prepreg", having a very small amount of resin already inside the sheet before applying. In the latter case, the amount of resin is not sufficient for polymerization. For these types of sheets the application of the adhesive is required to both bond the sheet to the concrete and to impregnate the sheet.

Table (2.1): Main characteristics and typical aspects of FRP composites, basic technique (Setunge, 2002)

	Pre-cured (Prefab)	**Cured in situ (Wet lay-up)**
Shape	Strips or laminates	Sheets or fabrics
Thickness	About 1.0 to 1.5 mm	About 0.1 to 0.5 mm
Use	Simple bonding of the factory made elements with adhesive	Bonding and impregnation of the sheets or fabrics with resin (shaped and cured in-situ)
Typical application aspects	If not pre-shaped only for flat surfaces	Regardless of the shape, sharp corners should be rounded
	Thixotropic adhesive for bonding	Low viscosity resign for bonding and impregnation
	Normally 1 layer, multiple layers possible	Often multiple layers
	Stiffness of strip and use of thyrotrophic adhesive allow for certain surface unevenness	Often a putty is needed to prevent deboning due to unevenness
	Simple in use, higher quality	Very flexible in use, needs
	guarantee (prefab system)	rigorous quality control
	Quality control (wrong application and bad workmanship loss of composite action between FRP EBR and substrate structure, lack of long term integrity of the system etc)	

2.7 Previous Works in the FE Modeling of RC Columns Strengthened with CFRP.

(Tavio & Tata, 2009) worked on predicting nonlinear behavior and stress-strain relationship of rectangular strengthened reinforced concrete columns with ANSYS. a nonlinear finite element modeling and analysis of rectangular normal-strength reinforced concrete columns strengthened with transverse steel under axial compressive loading. In this study, the columns were modeled as discrete elements using ANSYS nonlinear finite element software. Concrete was modeled with 8-noded SOLID65 elements that can translate either in the x-, y-, or z-axis directions from ANSYS element library. Longitudinal and transverse steels were modeled as discrete elements using 3D-LINK8 bar elements available in the ANSYS element library. The nonlinear constitutive law of each material was also implemented in the model. The results indicate that the stress-strain relationships obtained from the analytical model using ANSYS are in good agreement with the experimental data. This has been confirmed with the insignificant difference between the analytical and experimental, i.e. 5.65 and 2.80 percent for the peak stress and the strain at the peak stress, respectively. The comparison shows that the ANSYS nonlinear finite element program is capable of modeling and predicting the actual nonlinear behavior of strengthened concrete column under axial loading. The actual stress-strain relationship, the strength gain and ductility improvement have also been confirmed to be satisfactorily.

(Saravanan, 2014) worked on analytical modeling for confinement of high strength concrete columns with glass fiber reinforced polymer wrapping fiber reinforced polymer strengthened columns have been developed for new construction rehabilitation of concrete structures such as piers or piles in civil engineering field. The design oriented confinement model predominant in designing FRP strengthened concrete columns. The design model is directly based on in interpretation of experimental result. In this study one model is presented for reinforced concrete columns externally reinforced with fiber reinforced polymer wraps using finite element method adopted by ANSYS software. The finite element model was developed using for concrete and the three dimensional layer elements for the fiber reinforced polymer composites. The result obtained from those finite element analysis results were compared on the experimental data for respective concrete column with different conditions from researcher. The prediction of ANSYS model agreed with the experimental results.

(Julien & Emmanuel, 2015)Worked on experimental study on rc columns retrofitted by frp and subjected to seismic loading. Evaluate the strength and ductility enhancement resulting from the use of longitudinally bonded FRP. For this purpose, the paper presents the results of experimental investigation conducted on six real scale RC columns tested under a quasi-static loading path intended to be representative of a seismic solicitation: reversed lateral cyclic loading and constant axial load. The main parameter tested was the FRP configuration. Those tests helped us to analyze the behavior of RC columns depending on the FRP confinement (CFRP jacket) and on flexural reinforcement (carbon plates) and allowed us to determine the influence of these parameters on the ultimate strength, on ductility, on stiffness, on dissipated energy, and then to conclude about the behavior of the externally reinforced columns.

(Barbato & Hu,D., 2014) Worked on simple and efficient finite element modeling of reinforced concrete columns strengthened with fiber-reinforced polymers a frame finite element (FE) that is able to accurately estimate the load-carrying capacity and ductility of reinforced concrete (RC) circular columns strengthened with externally-bonded fiber-reinforced polymers (FRP). This frame FE can model collapse mechanisms due to concrete crushing, reinforcement steel yielding, and FRP rupture. The adopted FE considers distributed plasticity with fiber discretization of the cross-sections in the context of a force-based formulation, and uses advanced nonlinear material constitutive models for reinforcing steel and unstrengthened, steel-strengthened, and FRP-strengthened concrete.

(Jijin & Preetha, 2012) Worked on effect of gfrp jacketing & cfrp jacketing on rc columns of different cross-sectional shapes frp is an advanced composite material (ACM) that is relatively new material to civil engineering. It holds a better choice than reinforcing steel in certain applications. In order to attain large deformation before failure occurs and to enhance an adequate load resistance capacity, RC columns has to be laterally jacketed. Jacketing RC column with FRP improves column performance not only by carrying some fraction of axial load applied to it but also by providing lateral confining pressure to the column externally. In this work effect of circular, rectangular and square columns on GFRP jacketing and CFRP jacketing having same cross-sectional area were analysed. RC columns were analysed in ANSYS 15. The percentage area reduction of concrete in RC columns when FRP jacketing is provided is found out.

(Feng, 2002) worked on experimental research and finite element analysis of square concrete columns strengthened by FRP sheets under uniaxial compression In order to investigate the behavior of square concrete columns strengthened by fiber reinforced polymer (FRP) sheets, five specimens were tested and analyzed using finite element method (FEM). The loading behaviors of the strengthened concrete columns under uniaxial compression can be divided into three phases. As confirmed by experimental results, finite element analysis (FEA) can effectively simulate the behavior of square columns strengthened by FRP sheets when the proper numerical model is adopted. Based on the test and FEA, the stress distributions and the stress development are obtained. This provides theoretical understanding for establishing the stress-strain curve model. It is suggested that the FEM is a powerful method for further research on numerical test and parameter analysis.

(Prabhakaran, 2015) worked on comparative study on gfrp jacketed rc columns and cfrp jacketed rc columns of different shapes . Column jacketing with FRP sheets plays an important role in enhancing the performance of RC column. FRP is an Advanced Composite Material (ACM) that is relatively new material to civil engineering. It holds a better choice than reinforcing steel in certain applications. In order to attain large deformation before failure occurs and to enhance an adequate load resistance capacity, RC columns has to be laterally jacketed. Jacketing RC column with FRP improves column performance not only by carrying some fraction of axial load applied to it but also by providing lateral confining pressure to the column externally. In this work a comparative study on GFRP jacketed RC columns and CFRP jacketed RC columns of different shapes having same cross-sectional area were analyzed. Buckling analysis on RC columns of circular, rectangular and square cross-sectional shapes has been done in ANSYS 15. FRP Jacketing increases the load carrying capacity of all RC columns. CFRP Jacketed RC columns shows a better load carrying capacity than GFRP Jacketed RC Columns when both axial and eccentric loadings were applied in circular, rectangular and square cross-sectional shapes.

(Athanasios, Theodoros, & Georgia, 2007) worked on three-dimensional finite element analysis of reinforced concrete columns strengthened by fiber reinforced polymer sheets . an analytical investigation of concrete columns with conventional longitudinal and transverse steel reinforcement and external confinement by FRP sheets is performed. The study focuses on the behavior of old type columns with extremely low concrete strength and stirrup spacing leading to bars' elastic buckling failure when compressed. The investigation includes also viability of the use of external FRP confinement in delaying or preventing elastic buckling of bars under compression. A Drucker – Prager type model with an advanced approach in estimating plasticity parameters is inserted in finite element (FE) code. Results from numerical analyses are compared against performed experiments. Stress concentrations in concrete core and on FRP jacket are also investigated for analyses cases that have been carried out.

(Hajsadeg & Alaee, 2010) worked on numerical analysis of rectangular reinforced concrete columns strengthened with FRP jacket under eccentric loading . The paper is devoted to investigate the behavior of square RC columns strengthened with FRP wraps using ANSYS software. A total of four prisms of size 150×300×500mm and 210×210×500mm were simulated by the FE model and the results were compared with the experimental test results reported in literature. Very good agreement was found between the model results and the test results. Therefore, the mod-el was validated. As predicted, it was found that the effectiveness of FRP jackets under eccentric loads is re-duced in comparison with concentric loads. In the next step, the interaction diagrams of axial force and bend-ing moment for columns strengthened with FRP wrap was obtained from the model results. They were compared with the interaction diagrams proposed by the design guideline of ACI 440.2R-08. It was found that the load carrying capacities resulted from the model are generally higher than those recommended by ACI 440.2R-08.

2.8 Concluding Remarks

1. The studies showed that FRP effective in strengthening the concrete columns
2. Some of the researcher use ANSYS to develop their models
3. The FRP jacketing is a very good alternative for strengthening of existing square, circular and rectangular RC column and it helps in economical construction by concrete reduction in designing new RC columns
4. Finite element analysis is used to study the mechanical behaviour of reinforced concrete columns with bars suffering from premature buckling under compression as well as the effect of external confinement by FRP sheet jacket.

5. The model provides accurate prediction for concrete columns under uniform elastic confinement by FRP materials

CHAPTER 3

Numerical Modeling of Reinforced Concrete Material

CHAPTER 3

Numerical Modeling of Reinforced Concrete Material

3.1 Introduction

In this chapter, the mechanical behavior and finite element modeling basics of materials will be discussed as concrete, steel reinforcement, and carbon fiber reinforced polymer (CFRP) are presented. Further, failure criteria and modeling approaches for each material are introduced

3.2 Mechanical Behavior of Materials

The mechanical behavior of concrete , steel plates , steel reinforcement and FRP are explained in the following sections .

3.2.1 Concrete

3.2.1.1 Reinforced Concrete in Compression

Concrete as a material consists of hard particles of rocks mixed with cement paste to glue these particles together. When the concrete is subjected to compression, the stresses will seek through the hard particles. In compression the concrete starts to crack when the capacity of the glue between the particles is reached. This happens long before the strength of the concrete is exceeded.

At first the cracks are micro cracks between the hard particles and the paste. The micro cracks are the reason for some of the strains in the concrete. They will continue to develop, and at some point they become macro cracks and a fracture occurs. The stiffness of concrete decreases as the number of cracks increases. This is called the softening of the concrete, and it is the reason for the concave response of the material. When dealing with compression in reinforced concrete . A compression response for normal strength concrete is shown on Figure (3.1). The figure also shows important parameters for modelling with concrete in compression.

To calculate the stiffness for a certain stress in the concrete the secant modulus of elasticity has to be known. Approximate values for the secant modulus E = 0-0.4as listed in the design codes.

The compressive strength of the concrete is fan and the modulus of elasticity at this stress level is shown as E on the figure (3.1). (Rasmussen, 2012)

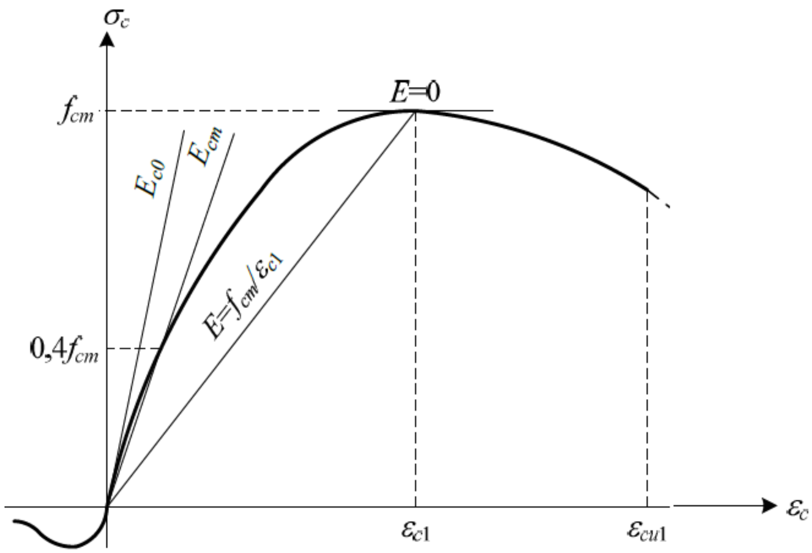


Figure (3.1): Response of concrete in compression

3.2.1.2 Reinforced Concrete in Tension

The first part of the stress-strain curve resembles the response of the uncracked concrete. The compatible strains in the concrete and reinforcement result in a linear elastic response, where the influence of the reinforcement is, most often, insignificant .The strain capacity is negative in the beginning due to shrinkage.

The second part of the curve starts when the tensile capacity of the concrete is reached, and the concrete starts to crack. The cracks will form one by one at locations where the concrete's strength is exceeded. Where the cracks form, the stress level in the concrete will drop, because the reinforcement is taking over. Due to this, the stress distribution in the steel and concrete in the length of the member is no longer uniform.

While cracks are forming, there will still be concrete tensile stresses in the cracked sections. As the width of the cracks become larger, stresses will decrease. They vanish when there is no more cohesion in a crack. At this point the reinforcement has taken over completely in the cracked sections. The decrease of the concrete's stiffness due to cracking is called the softening of the concrete.

In the areas between adjacent cracks the concrete is still able to carry tensile stress, because stress in the reinforcement is transmitted to the concrete by means of bond shear stresses. This is the effect called tension stiffening, which indicates that the concrete applies stiffness to the member in addition to the stiffness of the bare reinforcement. (Rasmussen, 2012)

When the applied load increases, the amount of tension stresses in the concrete will decrease with the increase in number of cracks, because more areas become crack zones. The tension-stiffening effect will also be decreased due to internal cracking.

At a certain level the member will stabilize and no more cracks will form. The tension-stiffening effect will drop and the response of the member will approach the one of a fully cracked when the reinforcement swim to yield. Around when yielding the reinforcement happens the elongated of the reinforcement bar will affects the bond strength.

The bar thickness has been reduced due to Poisson's ratio and therefore the bond strength is reduced as well. Due to additional stiffness from the concrete between cracks, the response will never be coincident with the bare reinforcement bar, (Rasmussen, 2012)

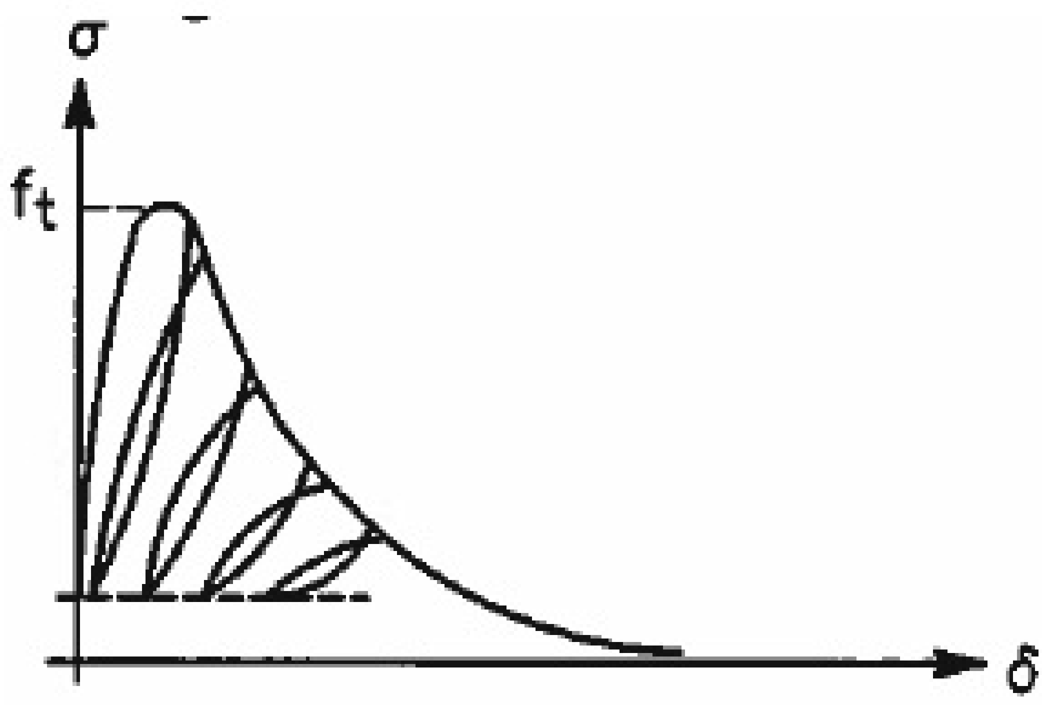


Figure (3.2): Stress-deflection relation for concrete in tension

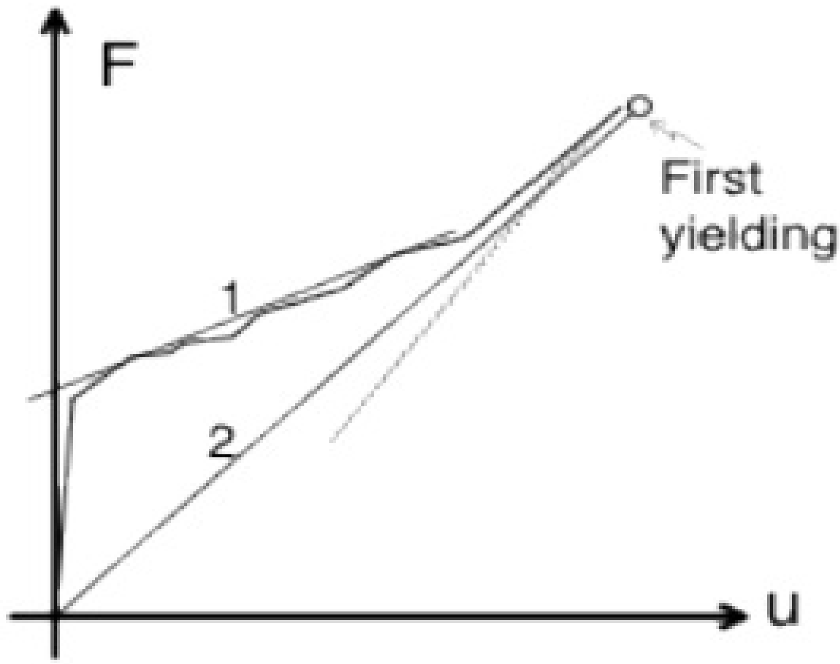


Figure (3.3): Stress-deflection relation for reinforced tension.

3.2.2 Steel Reinforcement

Figure (3.4) shows a typical stress-strain relationship for reinforcing steel. Steel is initially linear-elastic for stress less than the initial yield stress. At ultimate tensile strain, the reinforcement begins to neck and strength is reduced. At a maximum strain, the steel reinforcement fractures and load capacity is lost.

This steel response may be defined by a few material parameters. These include the elastic modulus (E_s), the yield strength (f_y), the strain at which peak strength is achieved (ε_u), the peak strength (f_u), the strain at which fracture occurs (ε_{max}), and the capacity prior to steel fracture (f_s), (ASTM A615, 1995).For general engineering applications, an elastic-plastic constitutive relationship, either with or without strain hardening, is normally assumed for ductile reinforcing steel.

In an elastic hardening model it is assumed that steel shows some hardening after it yields.An elastic-perfectly plastic model generally yields acceptable results for the response prediction of RC members (Neale, Ebead, Abdel Baky, Elsayed, & Godat, 2005).

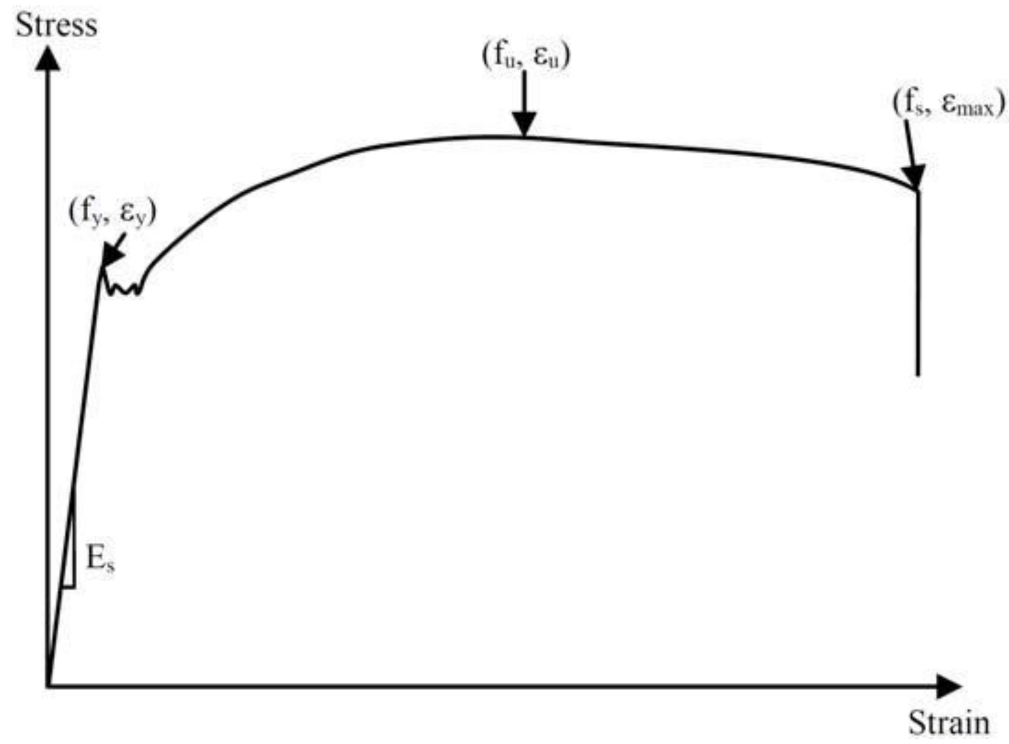


Figure (3.4): Tensile Stress-strain Curve for Typical Reinforcing Steel Bar (ASTM A615, 1995)

3.2.3 Fiber Reinforced Polymer (FRP)

FRP composite materials are not homogeneous. Their properties are dependent on many factors, the most important of which are, (ISIS, 2006):

1. The relative proportions of fiber and matrix (volume fractions).
2. The mechanical properties of the constituent materials (fiber, matrix, and any additives).
3. The orientation of the fibers within the matrix.
4. The method of manufacture

Figure (3.5) shows typical stress-strain curves for fibers, matrices, and the FRP materials that result from the combination of fibers and matrix.

Unidirectional FRP materials are typically linear elastic up to failure, and do not exhibit the yielding behavior that is displayed by conventional reinforcing steel, (ISIS, 2006).

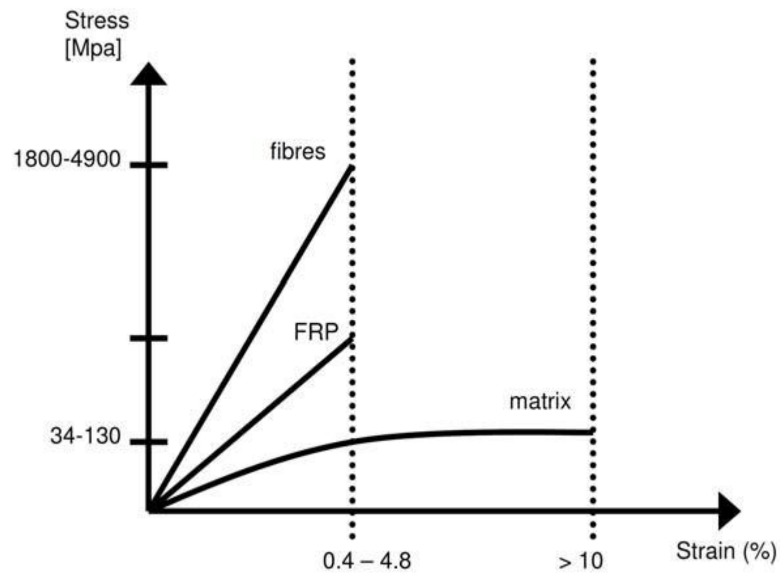


Figure (3.5): Stress-Strain Relationships for FRP, (ISIS, 2006).

3.3 Finite Element Modeling of Materials

The finite element modeling of materials are explined in following sections , crack models are explained for materials but it weren't taken in the validation of results.

3.3.1 Finite Element Modeling of Concrete

The uniaxial stress-strain behavior of concrete in compression is shown in Figure (3.6).Various mathematical models are available to approximate this nonlinear behavior namely: linearly elastic-perfectly plastic model, inelastic- perfectly plastic, Hognestad, and piecewise linear model. In the present study a modified Hognestad mathematical model figure(3.7) has been used for the approximation of the stress-strain behavior of concrete,

1. Initial tangent modulus of elasticity increases with an increase in compressive strength. So, the elastic modulus (Ec) is given by (ACI 8.5.1):

$$Ec = 4700\sqrt{f_c'} \qquad (3-1)$$

Where f_c is compressive strength of concrete at 28 days in MPa. The stress-strain relation initially must satisfy the Hooke's law.

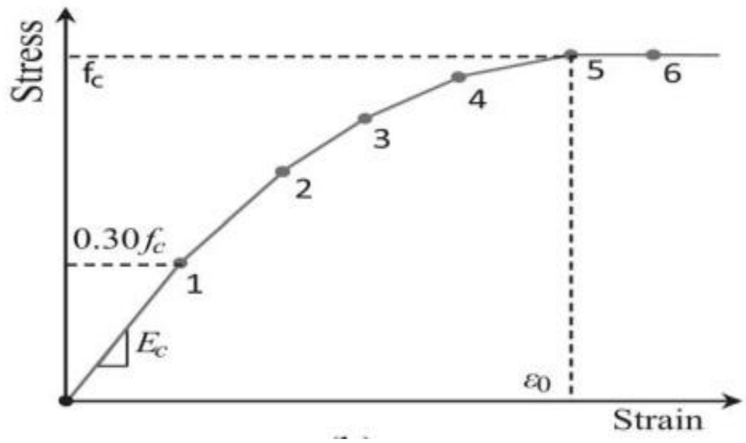


Figure (3.6): Uniaxial Stress-Strain Behavior of Concrete

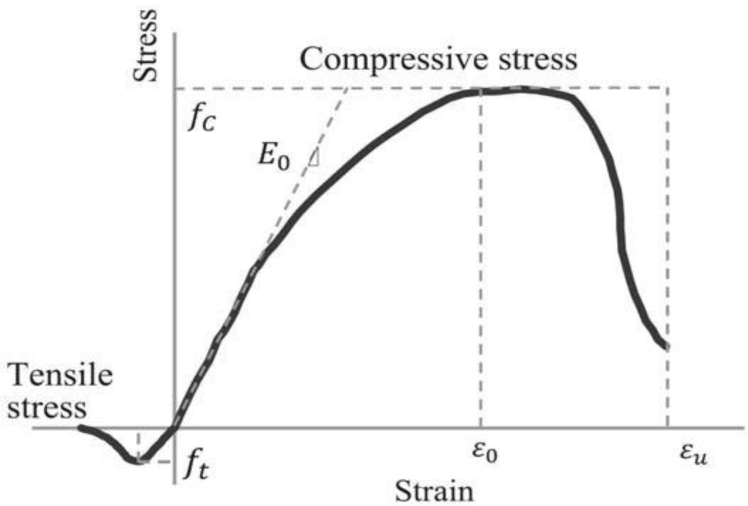


Figure (3.7): Modified Hognestad Model (Basappa & and Rajagopal, 2013)

2. The strain at maximum stress increases as the compressive strength increases:

$$\varepsilon_o = \frac{2f_C}{Ec} \qquad (3\text{-}2)$$

3. The raising portion of the stress strain curve resembles a parabola with vertex at the maximum stress:

$$f = \frac{E_C \ \varepsilon}{1+(\frac{\varepsilon}{\varepsilon_0})^2} \qquad (3\text{-}3)$$

Where, (f) is stress for a value of strain in stress-strain relationship of concrete. The stress-strain behavior of concrete under tension includes raising part and descending part. The raising part is slightly curved, approximated either as straight lines or parabola. The descending part drops rapidly with increased elongation after the maximum stress is crossed.

3.3.2 Finite Element Modeling of Cracks in Concrete

3.3.2.1 Discrete crack model

The discrete crack model assumes a separation between element edges. The approach suffers from two drawback. First, it implies a continuous change in nodal connectivity, which does not fit the nature of the finite element displacement method. Secondly, the crack is constrained to follow predefined path along the element edges. A class of problems exists, however, whereby the orientation of the discrete crack is not necessarily the prime subject of interest. One may think of fracture in the form of a straight separation band, the location of which is known in advance, or of discrete cracks along the interface between concrete and reinforcement. Furthermore, engineering problems exist whereby a mechanism of discrete cracks can be imagined to occur in a fashion similar to yield line mechanisms. For suck cases, the above drawbacks vanish and one may use a simple form of discrete cracks with a predefined orientation.

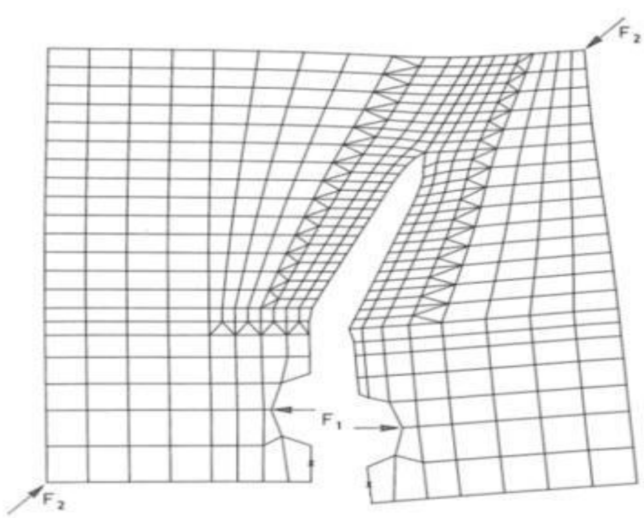


Figure (3.8): Change in Topology of Finite Elements

With the change of topology and the redefinition of nodal points, the narrow bandwidth of the stiffness matrix is destroyed and a greatly increased computational effort results in this model figure(3.8). Moreover, the lack of generality in crack orientation has made the discrete crack model unpopular. In spite of these shortcomings, the use of discrete crack models in finite element analysis offers

certain advantages over the other methods. For those problems that involve a few dominant cracks, the discrete crack approach offers a more realistic description of the cracks, which represent strain discontinuities in the structure. Such discontinuities are correctly characterized by the discrete crack model (Kotsovos & Pavlovic, 1995).

3.3.2.2 Smeared Crack Model

The need for a crack model that offers automatic generation of cracks and complete generality in crack orientation, without the need of redefining the finite element topology, has led the majority of investigators to adopt the smeared crack model. Rather than representing a single crack, the smeared crack model represents many finely spaced cracks perpendicular to the principal stress direction.

This approximation of cracking behavior of concrete is quite realistic, since the fracture behavior of concrete is very different from that of metals. In concrete fracture is preceded by microcracking of material in the fracture process zone, which manifests itself as strain softening. This zone is often very large relative to the cross section of the member due to the large size of aggregate.

With this continuum approach, the local displacement discontinuities at cracks are distributed over some tributary area within the finite element. In contrast to the discrete crack concept, the smeared crack concept fits the nature of the finite element displacement method, since the continuity of the displacement field remains intact.

Although this approach is simple to implement and is, therefore, widely used. It has nevertheless a major drawback, which is the dependency of the results on the size of the finite element mesh used in the analysis. When large finite elements are used, each element has a large effect on the structural stiffness. When a single element cracks, the stiffness of the entire structure is greatly reduced. Higher order elements in which the material behavior is established at a number of integration points do not markedly change this situation, because, in most cases, when a crack takes place at one integration point, the element stiffness is reduced enough so that a crack will occur at all other integration points of the element in the next iteration. Thus, a crack at an integration point does not relieve the rest of the material in the element, since the imposed strain continuity increases the strains at all other integration points.

The overall effect is that the formation of a crack in a large element results in the softening of a large portion of the structure. The difficulty stems from the fact that a crack represents a strain discontinuity, which cannot be modeled correctly within a single finite element in which the strain varies continuous.

Smeared crack models can be categorized into: 1. Fixed smeared crack model as shown figure(3.9), 2. Rotating smeared crack model as shown figure(3.10). The Orientation of a crack in the fixed smeared crack model is fixed during the entire computational process. While, a rotating smeared crack model allows the orientation of the crack to co-rotate with the axes of principal strain (Rots & Blaauwendraad, 1989).

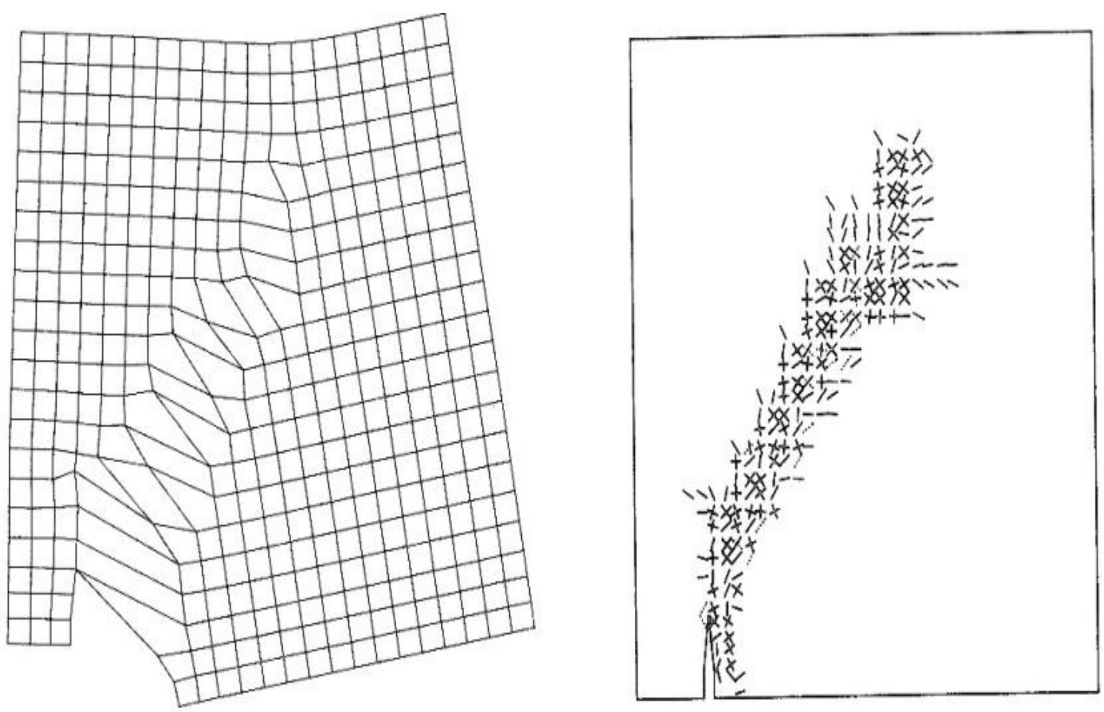


Figure (3.9): Fixed Crack Model

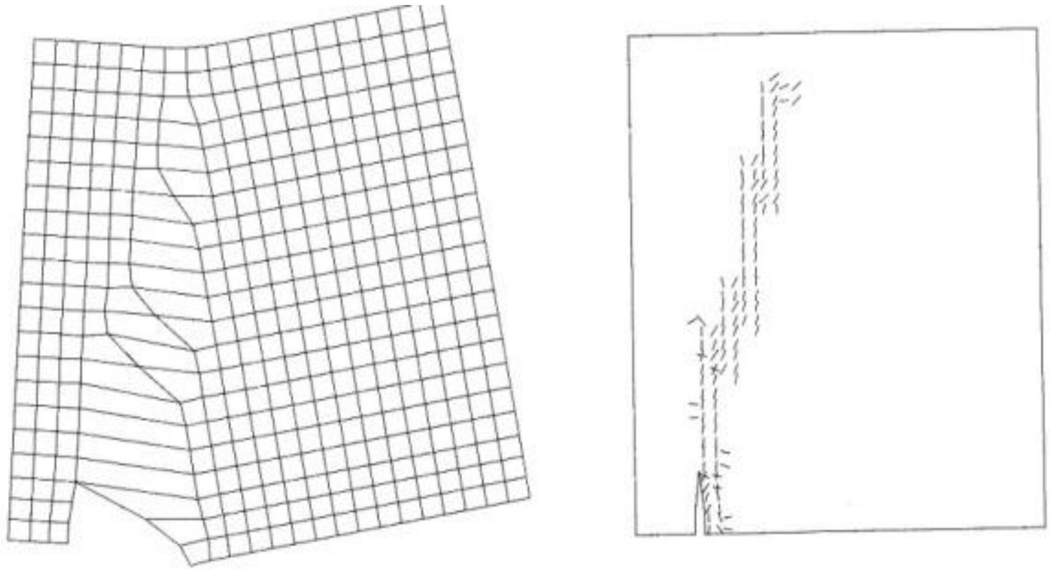


Figure (3.10): Rotated Crack Model

3.3.3 Finite Element Failure Criteria of Concrete

Figure (3.11) represents the 3- D failure surface for states of stress that are biaxial or nearly biaxial. If the most significant nonzero principal stresses are in the σ_{xp} and σ_{yp} directions, the three surfaces presented are for σ_{zp} slightly greater than zero, σ_{zp} equal to zero, and σ_{zp} slightly less than zero.

Although the three surfaces, shown as projections on the σ_{xp} - σ_{yp} plane, are nearly equivalent and the 3-D failure surface is continuous, the mode of material failure is a function of the sign of σ_{zp}. For example, if σ_{xp} and σ_{yp} are both negative and σ_{zp} is slightly positive, cracking would be predicted in a direction perpendicular to the σ_{zp} direction. However, if σ_{zp} is zero or slightly negative the material is assumed to crush, (ANSYS, 2014).

In ANSYS, a concrete element cracks when the principal tensile stress in any direction lies outside the failure surface. After cracking, the elastic modulus of the concrete element is set to zero in the direction parallel to the principal tensile stress direction.

Crushing occurs when all principal stresses are compressive and lie outside the failure surface; subsequently, the elastic modulus is set to zero in all directions and the element effectively disappears, (ANSYS, 2014).

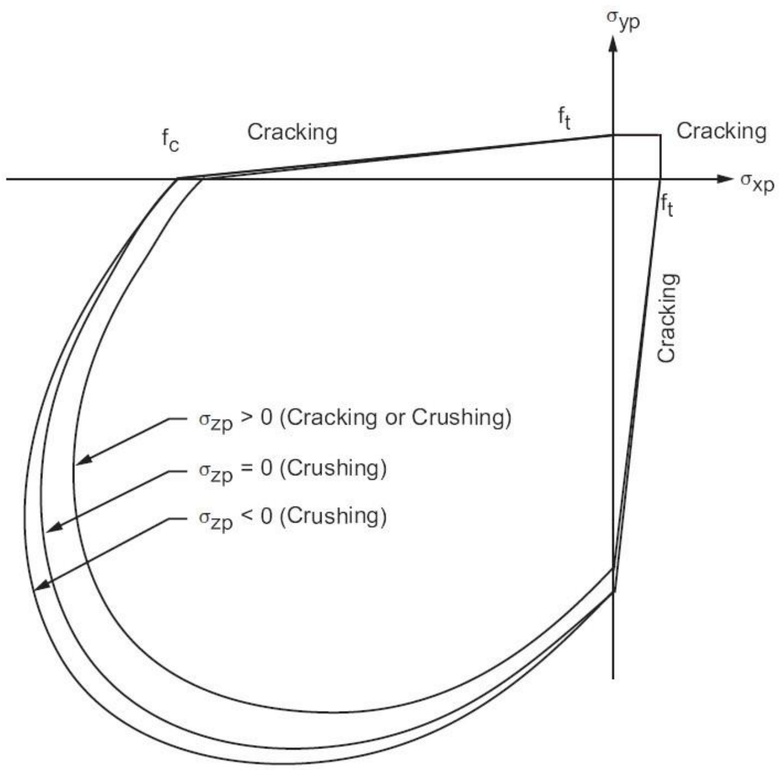


Figure (3.11): 3D failure Surface for Concrete, [ANSYS 2014].

3.3.4 Reinforcing Steel Models

Modeling steel reinforcement is much easier than modeling concrete since it is not environmental conditions or time dependent. A uniaxial stress-strain relationship would suffice to define the material properties needed to carry out the analysis of reinforced concrete structures. For practical purposes, reinforcing steel exhibit the same behavior in tension as in compression,. The behavior of steel exhibits a linear elastic behavior as shown in figure (3.12). Since steel reinforcement is used in concrete construction in the form of reinforcing bars or wire, it is not necessary to introduce the complexities of three-dimensional constitutive relations for steel. For computational convenience, it even often suffices to idealize the one dimensional stress-strain relation for steel.

Reinforcing steel can be modeled as:

1. Smeared model
2. Embedded model
3. Discrete model

In the Smeared model, the reinforcing steel is assumed to be distributed over the concrete element at a certain orientation angle. A composite concrete-steel constitutive relation is used in this case, which, however, requires that perfect bond be assumed between concrete and steel. An embedded steel model is useful in connection with higher order isoparametric concrete elements.

The reinforcing steel is considered as an axial member built into the isoperimetric element such that its displacements are consistent with those of the element. Such a model again implies perfect bond between concrete and steel. A drawback to this model is the high computational effort and time required to the analysis. The most widely used model represents the reinforcement with discrete one-dimensional truss elements, which are assumed to be pin connected and possess two degrees of freedom at each node. Alternatively, column elements can also be used, in which case, three degrees of freedom are allowed at each end of the bar element. In either case, the one-dimensional reinforcing bar elements can be easily superimposed on the two-dimensional concrete element mesh.

A significant advantage of the discrete representation, in addition to its simplicity, is that it can include the slip of reinforcing steel with respect to the surrounding concrete.

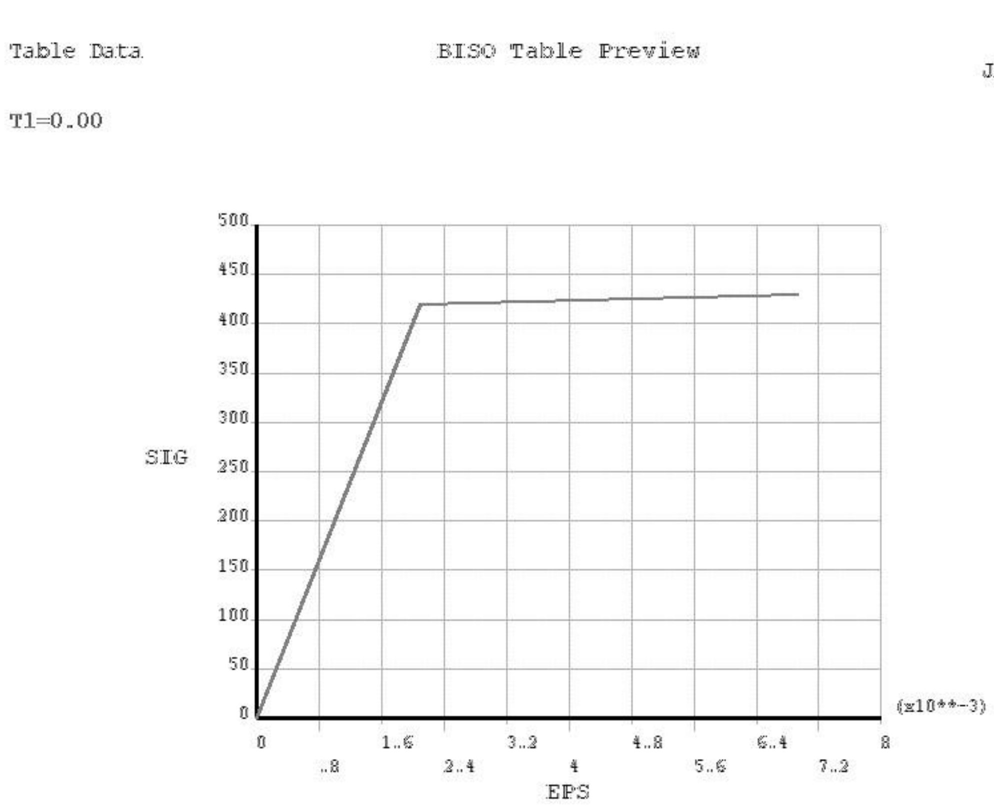


Figure (3.12): Linear Elastic-Perfect Plastic Model

3.3.5 Finite Element Modeling of FRP

the unidirectional lamina has three mutually orthogonal planes of material properties (i.e., xy, xz, and yz planes). The xyz coordinate axes are referred to as the principal material coordinates where the x direction is the same as the fiber direction, and the y and z directions are perpendicular to the x direction. It is a so-called orthotropic material, [Barbero,2014, Kaw, 2006]. CFRP composites can be modeled either using isotropic linear elastic model or orthotropic linear elastic model (Mohammad H. , 2015), In this study, the properties of the CFRP composites were nearly the same in any direction perpendicular to the fibers. Thus, the properties in the y direction were the same as those in the z direction. Orthotropic linear elastic model for CFRP composites was used throughout this study.

Failure criteria are used to assess the possibility of failure of a material. Doing so allows the consideration of orthotropic materials, which might be much weaker in one direction than another, (ANSYS Mechanical APDL Manual Set, 2014).

Failure criteria are used to learn if a layer has failed due to the applied loads. Many failure criteria are used in FE software packages for composite materials. The most used criteria are: maximum strain failure criteria, maximum stress failure criterion, Tsai-Wu failure criteria, and physical failure criteria, like: Hashin fiber failure criterion, Hashin matrix failure criterion, Puck fiber failure criterion, and Puck matrix failure criterion (ANSYS Mechanical APDL Manual Set, 2014).

CHAPTER 4

BUILDING OF ANSYS FINITE ELEMENT MODELS

CHAPTER 4
BUILDING OF ANSYS FINITE ELEMENT MODELS

4.1 Introduction

The finite element method is a numerical analysis technique for obtaining approximate solutions to a wide variety of engineering problems. ANSYS is a general purpose finite element modeling package for numerically solving a wide variety of problems which include static/dynamic structural analysis (both linear and nonlinear), heat transfer and fluid problems, as well as acoustic and electro-magnetic problems.

The external strengthening of reinforced concrete columns with carbon fiber reinforced polymers (CFRP) had been analyzed using finite element models in ANSYS 14. Many self-learning tutorials and manuals were used as references in preparing the FE models using ANSYS.

The experimental investigations were used to model and verify the strengthening of RC column with CFRP using ANSYS. (Mohammad, Farshid, & Amir, 2010)

4.2 Modeling Assumptions

The following are the modeling assumptions made column models in the present study to provide reasonably good simulations for columns the complex behavior:

1. Concrete and steel are modeled as isotropic and homogeneous materials.
2. Poisson's ratio is assumed to be constant throughout the loading history.
3. Steel is assumed to be an elastic-perfectly plastic material and identical in tension and compression.
4. Perfect bond exists between concrete and steel reinforcement.
5. Perfect bond exists between concrete and CFRP fabric. The perfect bond assumption used in the structural modeling doesn′t cause a significant error in the predicted load-deflection response.
6. The CFRP material is assumed to be especially orthotropic-transversely isotropic. That is, the material properties in the two directions that are both perpendicular to the fiber direction are identical.
7. The CFRP fabric is assumed to carry stress along its axis only.

8. Time-dependent nonlinearities such as creep, shrinkage, and temperature change are not included in this study.

4.3 Selection of Element Types Using ANSYS

In this section, the description of element types used for all materials used in ANSYS models is presented. These materials are: concrete, steel reinforcement, and carbon fiber reinforced polymer (CFRP). Elements used in thesis models are widely used and recommended by ANSYS and previous researchers.

4.3.1 Concrete

An eight-node solid element, Solid65, was used to model the concrete. The solid element has eight nodes with three degrees of freedom at each node: translations in the nodal local x, y, and z directions. The element is capable of plastic deformation, cracking in three orthogonal directions, and crushing. The geometry and node locations for this element type are shown in Figure (4-1), (ANSYS Mechanical APDL Manual Set, 2014).

4.3.2 Steel Reinforcement

A Link180 element was used to model steel reinforcement. The element is a uniaxial tension-compression element with three degrees of freedom at each node: translations in the nodal x, y, and z directions. Plasticity, creep, rotation, large deflection, and large strain capabilities are included. This element is shown in Figure (4-2), (ANSYS Mechanical APDL Manual Set, 2014).

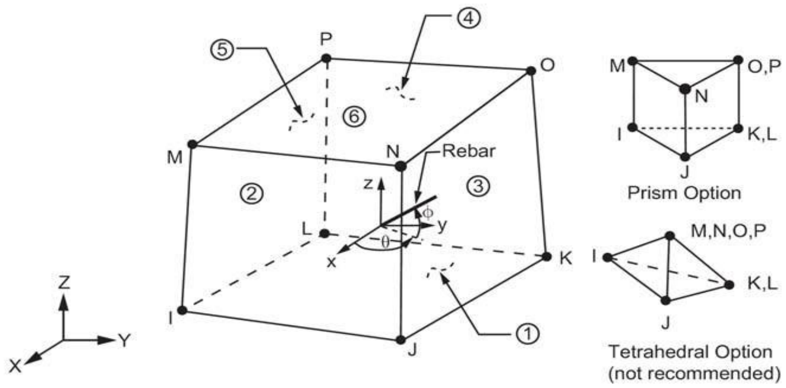


Figure (4.1): Solid65 Geometry (ANSYS Mechanical APDL Manual Set, 2014)

4.3.3 Loading and Supporting Steel Plates

The Solid185 element is used for the modeling of loading and supporting steel plates. This element is defined by eight nodes having three degrees of freedom at each node: translations in the nodal x, y, and z directions. The element is capable of plasticity, hyperelasticity, stress stiffening, creep, large deflection, and large strain capabilitiess. This element is shown in Figure (4-3).

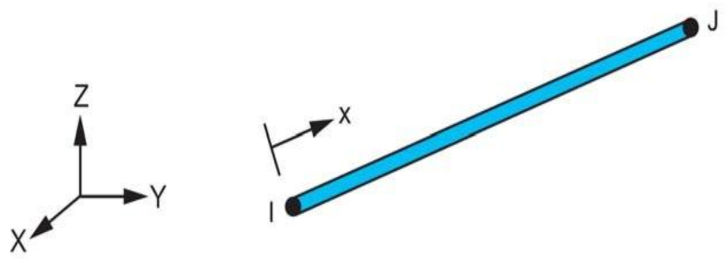


Figure (4.2): Link180 Geometry (ANSYS Mechanical APDL Manual Set, 2014)

4.3.4 Carbon Fiber Reinforced Polymer (CFRP)

Shell181 element is used for the modeling Carbon Fiber Reinforced Polymer (CFRP). It is a four-node element with six degrees of freedom at each node: translations in the x, y, and z directions, and rotations about the x, y, and z- axes. SHELL41 is well-suited for linear, large rotation, and/or large strain nonlinear applications. The geometry, node locations, and the coordinate system are shown in Figure (4-4), [ANSYS, 2014].

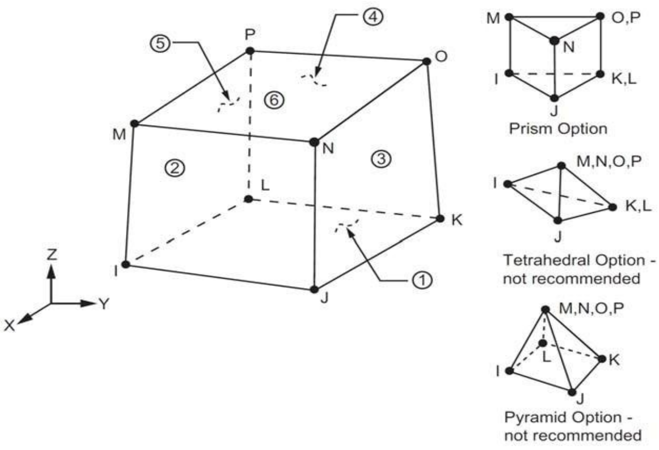


Figure (4.3): SOLID181 Homogeneous Structural Solid Geometry (ANSYS Mechanical APDL Manual Set, 2014)

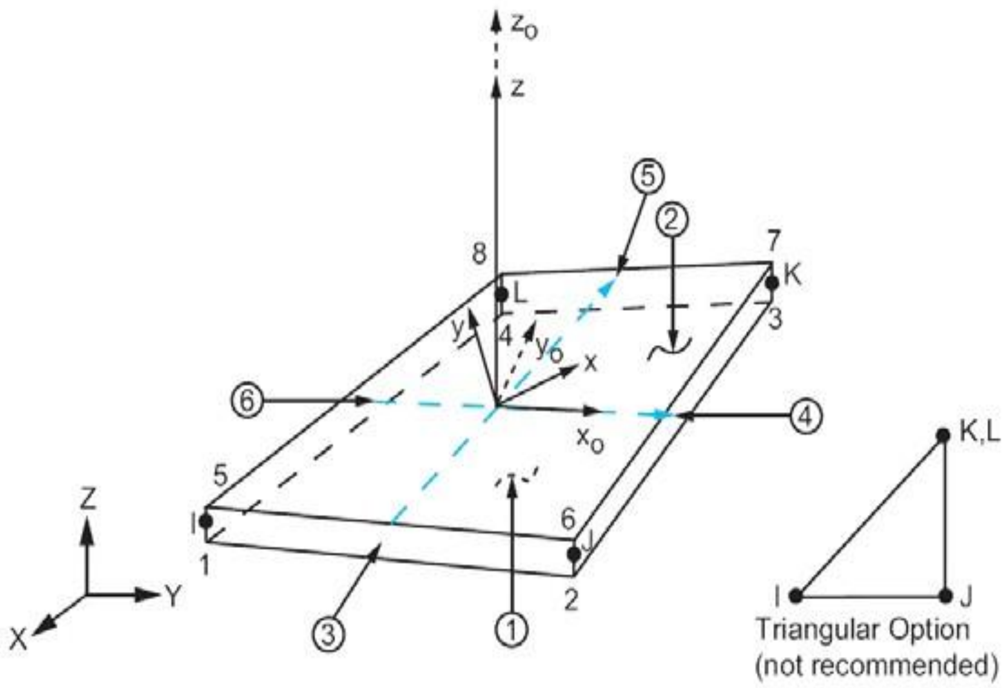


Figure (4.4): Shell181 Geometry (ANSYS Mechanical APDL Manual Set, 2014)

The element types used for modeling of model is summarized in Table (4-1).

Table (4.1): Element Types for ANSYS Models

Material Type	**ANSYS Element**
Reinforced Concrete	Soild65
Steel Reinforcement	Link180
Carbon Fiber Reinforced Polymer(CFRP)	Shell181

4.4 Material Properties

The following sections will be explained the matilials properties of finite elements model with ANSYS , and the failure criterias for each material .

4.4.1 Concrete

Material Model refers to the Solid65 element. The Solid65 element requires linear isotropic and multilinear isotropic material properties, in addition to selection of failure criteria of concrete.

4.4.1.1 Linear Isotropic Properties of Concrete

E_X is the modulus of elasticity of the concrete (E_c). It was based on equation (3-1), with a value of f_c' equal to 26.4 MPa. v_{XY} is the Poisson's ratio (ν). Poisson's ratio was assumed to be 0.25 .

4.4.1.2 Multilinear Isotropic Properties of Concrete

Modified Hognestad mathematical model (See Fig. 3-8) has been used for the approximation of the stress-strain behavior of concrete. Equations (3-2) and (3-3) were used to predict the multilinear isotropic stress strain curve for the concrete. The multilinear curve was used to help with convergence of the nonlinear solution algorithm, (Mohammad H. , 2015).

Figures (4-5) shows the stress-strain relationship used in this study for ANSYS model respectively. The curve starts at zero stress and strain. Point 2, defined as 0.3fc′, was calculated in the linear range.

Points from 3 to 20 were calculated from Eq. (3-3) with ε_o obtained from Eq. (3-2). Strains were selected and the stress was calculated for each strain. Point 20 is at f_c'. After Point 19, perfectly plastic behavior of concrete was assumed.

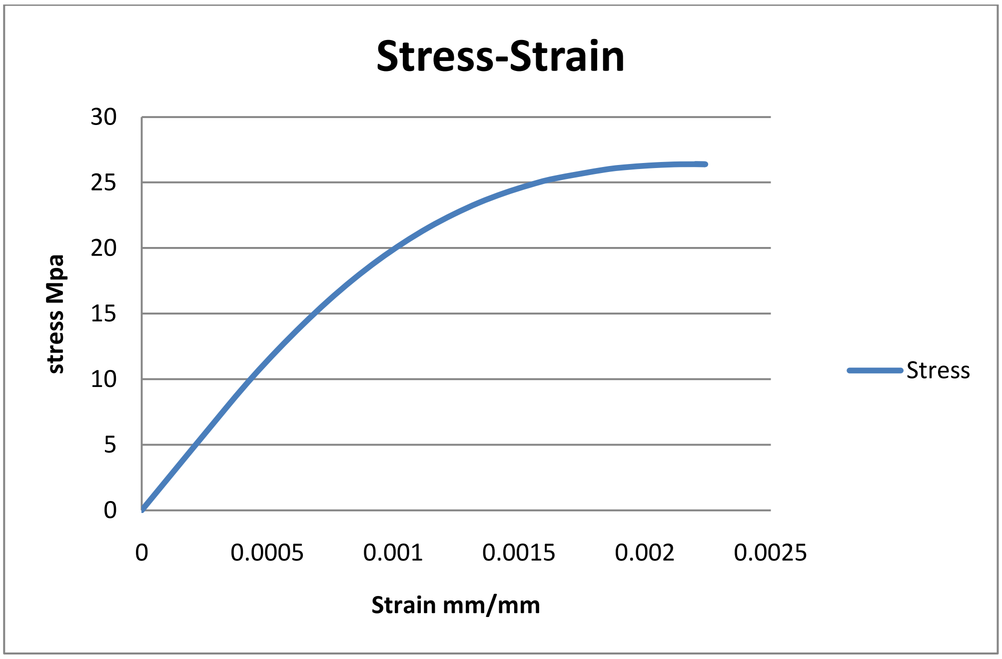


Figure (4.5): Compressive Uniaxial Stress-Strain Curve for Concrete

Parameters needed to define the material model for concrete in ANSYS models are shown in Tables (4-2).

Table (4.2): Material Properties of Concrete for ANSYS column Model

Element Type	Material Properties		
Soild65	Linear Isotropic		
	E_X	24500 (MPa)	
	v_{XY}	0.25	
Soild65	Multilinear Isotropic		
	Point	**Strain**	**Stress (MPa)**
	1	0	0
	2	0.00034	7.92
	3	0.00044	10.16
	4	0.00054	12.23
	5	0.00064	14.16
	6	0.00074	15.96
	7	0.00084	17.60
	8	0.00094	19.08
	9	0.00104	20.40
	10	0.00114	21.57
	11	0.00124	22.58
	12	0.00134	23.46
	13	0.00144	24.19
	14	0.00154	24.80
	15	0.00164	25.30
	16	0.00184	25.98
	17	0.00194	26.19
	18	0.00204	26.32
	19	0.00214	26.39
	20	0.0022	26.40

Table (4.2): Continue Material Properties of Concrete for ANSYS column Model

	Concrete	
	Open Shear Transfer Coef.	0
	Closed Shear Transfer Coef.	1
	Uniaxial Cracking Stress	2.7 MPa
	Uniaxial Crushing Stress	26.4 MPa
	Biaxial Crushing Stress	Default
	Hydrostatic Pressure	Default
	Hydro Biax Crushing Stress	Default
	Tensile Crack Factor	0.8

4.4.1.3 Failure Criteria of Concrete

Implementation of the Willam and Warnke (1975) concrete material model in ANSYS requires that different constants to be defined. These constants are: (ANSYS Mechanical APDL Manual Set, 2014)

1. Shear transfer coefficients for an open crack;
2. Shear transfer coefficients for a closed crack;
3. Uniaxial tensile cracking stress;
4. Uniaxial crushing stress (positive);
5. Biaxial crushing stress (positive);
6. Ambient hydrostatic stress state for use with constants 7 and 8;
7. Biaxial crushing stress (positive) under the ambient hydrostatic stress state (constant 6);
8. Uniaxial crushing stress (positive) under the ambient hydrostatic stress state (constant 6);
9. Stiffness multiplier for cracked tensile condition.

The shear transfer coefficient represents a shear strength reduction factor for subsequent loads that induce sliding (shear) across the crack face, [Chansawat et al., 2009]. Typical shear transfer coefficients range from 0.0 to 1.0, with 0.0 representing a smooth crack (complete loss of shear transfer) and 1.0 representing a rough crack (no loss of shear transfer), (ANSYS

Mechanical APDL Manual Set, 2014). For an open crack, the shear transfer coefficient varied between 0.05 and 0.50 in many studies of reinforced concrete structures, (Mohammad H. , 2015). In this study, many analysis attempts had been done to determine the appropriate values of shear transfer coefficients based on comparison of FE load-displacement values with experimental results. The open and closed cracks shear transfer coefficients used in this study for column models are shown in Tables (4-2).

The uniaxial cracking stress of concrete (tensile strength) is based upon the modulus of rupture. Modulus of rupture of concrete is a more variable property than the compressive strength and is about 8 to 15 percent of the compressive strength, (Mohammad H. , 2015). In ANSYS, when cracking occurs at an integration point of Solid65 element, material properties are adjusted to effectively model a "smeared band" of cracks, rather than discrete cracks.

When a principal stress at an integration point in a concrete element exceeds the tensile strength, stiffness is reduced to zero in that principal direction perpendicular to the cracked plane (ANSYS Mechanical APDL Manual Set, 2014). In this study, values of uniaxial cracking stress of concrete used for column models are shown in Tables (4-2).

In ANSYS, crushing of concrete element occurs when all principal stresses are compressive and lies outside the failure surface; subsequently, the elastic modulus is set to zero in all directions, and the element effectively disappears, (Mohammad H. , 2015). The uniaxial crushing stress of concrete in is based on the uniaxial compressive strength tested in the experimental investigations. The failure surface of concrete can be specified with a minimum of two constants, f_t and f_c. The remainder of the variables in the concrete model was left to default based on (Basappa & Rajagopa, 2013) equations.

4.4.2 Steel Reinforcement

Material model the Link180 element. Material model number 2 is used to model the reinforcement, while material model number 3 is used to model the stirrups.

The Link180 element is assumed to be bilinear isotropic and is based on the von Mises failure criteria, (ANSYS Mechanical APDL Manual Set, 2014). The bilinear model requires the

Yield Stress (f_y), as well as the Hardening Modulus (tangent modulus of the plastic region) of steel to be defined. Elastic Modulus (E_X) was also defined, and Poisson's Ratio (v_x) was assumed to be 0.3.Tables (4-3) show material properties of steel reinforcement used for ANSYS column models respectively.

Table (4.3): material properties of steel reinforcement

Element Type	**Material Properties**	
Link180	**Linear Isotropic**	
	E_X	200000 MPa
	v_{XY}	0.3
	Bilinear Isotropic	
	Yield stress	476 MPa
	Tangent Modulus	20 MPa
	Section (SECID: 1, SECTYPE: link Shell) (in ANSYS)	
Link180	**Linear Isotropic**	
	E_X	200000 MPa
	v_{XY}	0.3
	Bilinear Isotropic	
	Yield stress	345 MPa
	Tangent Modulus	20 MPa

The steel for the finite element models was assumed to be an elastic-perfectly plastic material and identical in tension and compression. Figure (4-6) shows the assumed stress-strain curve for steel reinforcement, (Mohammad H. , 2015).

4.4.3 Carbon Fiber Reinforced Polymer (CFRP)

Material model refer to CFRP fabric which was modeled using the shell181 element. CFRP composites were assumed to be especially orthotropic and transversely isotropic; that is, mechanical properties are the same in any direction perpendicular to the fibers. Definition of CFRP in ANSYS model requires definition of linear isotropic material properties, sectionproperties, and failure criteria. Parameters needed to define the material model for CFRP in ANSYS column models are shown in Tables (4-4).

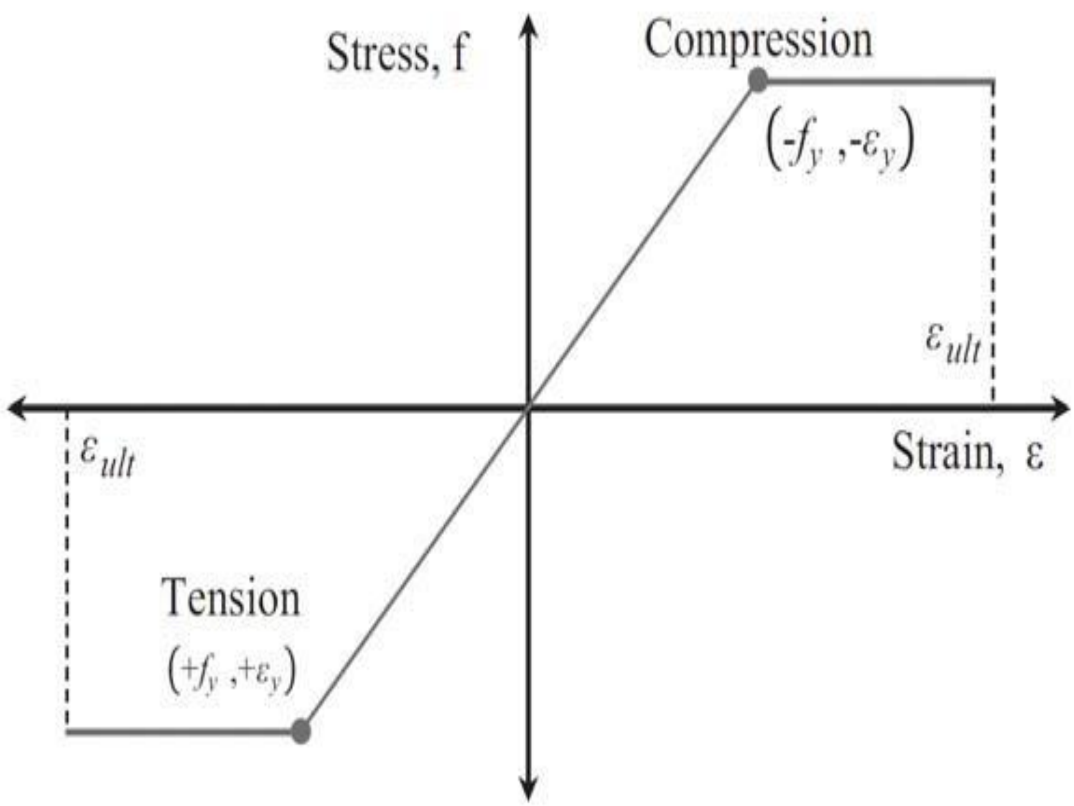


Figure (4.6):Stress-Strain Curve for Steel Reinforcement

4.4.3.1 Linear Orthotropic Properties

The stress-strain relationship of CFRP is roughly linear up to failure. In this study, it was assumed that the stress-strain relationship for the CFRP laminates is linearly elastic.

To define the linear orthotropic model of CFRP in ANSYS, the following properties are specified:

- Elastic modulus in three directions (E_X, E_Y and E_Z).
- Shear modulus for three planes (G_{XY}, G_{XZ} and G_{YZ}).
- Major Poisson's ratio for three planes (v_{XY}, v_{XZ} and v_{YZ}).

Table (4.4): Material Properties of CFRP for ANSYS.

Element Type	**Material Properties**	
Shell181	Linear Orthotropic	
	E_X	230000 MPa
	E_Y	12000 MPa
	E_Z	12000 MPa
	v_{XY}	0.3
	v_{YZ}	0.45
	v_{XZ}	0.3
	G_{XY}	7000 MPa
	G_{YZ}	7000 MPa
	Gv_{XZ}	7000 MPa
	Section (SECID: 3, SECTYPE: Shell)	
	Layer No. 1	
	Thickness of layer	0.165 mm
	Orientation	0 degree
	Failure Criteria	
	Stress – XTEN	3430 MPa
	Strain – XTEN	0.015

A local coordinate system for the CFRP shell element was defined where the x direction is the same as the fiber direction, while the y and z directions were perpendicular to the x direction.

The elastic modulus in the fiber direction of the unidirectional CFRP material used in the experimental studies was specified by the manufacturer, major Poisson′s ratio was assumed, and then, the elastic modulus in directions perpendicular to the fiber direction, minor Poisson′ ratio, and shear modulus were predicted using Rule of Mixture, as shown in tables (4-4) .

4.4.3.2 Section Properties

The most important characteristic of a composite material is its layered configuration. Each layer may be made of a different orthotropic material and may have its principal directions oriented differently. For laminated composites, the fiber directions determine layer orientation, (ANSYS Mechanical APDL Manual Set, 2014). To define the layered configuration of CFRP fabric, the following shall be specified:

- Number of layers.
- Thickness of each layer (TK).
- Orientation of the fiber direction for each layer (THETA).

4.4.3.3 Failure Criteria of CFRP

CFRP fabrics were modeled as linear elastic materials up to failure**.** Maximum strain failure criteria and maximum stress failure criteria were used based on the longitudinal tensile strength and maximum strain of the used CFRP fabrics,

4.5 Description of Experimental columns

In this section geometric details of column. The experimental investigation of (Mohammad, Farshid, & Amir, 2010)was used to simulate the strengthening model in ANSYS. This Experiment presents the results of the numerical analysis of square/rectangular reinforced concrete (RC) columns strengthened with FRP jackets. The size of column 250×250×500 mm was modeled and analysis was carried out using a non-linear finite element method. Two parameters of wrap thickness and fiber orientation were considered.

4.5.1 Geometry

By taking advantage of the symmetry of the column , a quarter of full column was used for modeling. This approach reduced computational time and computer disk space requirements significantly. The concrete column was modeled as volumes, CFRP layers were modeled as areas, and steel reinforcement were modeled as lines figure (4-7). Since a quarter of the column is being modeled, the model is 500 mm long, with a cross-section of 125 mm x 125 mm. The CFRP fabric layer bonded to the column soft was modeled as an areas. The quarter of the entire model including the created volumes for column model is shown in Figure (4-8).

4.5.2 Study Specimens Naming

To discuss my results , naming of models to show the results it is important as show in table (4-5)

Table (4.5): Study Specimens Naming

Name	Data	Number of layers
NS-R-1-200-0-40	Experimental	0
A-3	Experimental/Model	3
A-1	Model	1
A-3	Model	3
A-5	Model	5

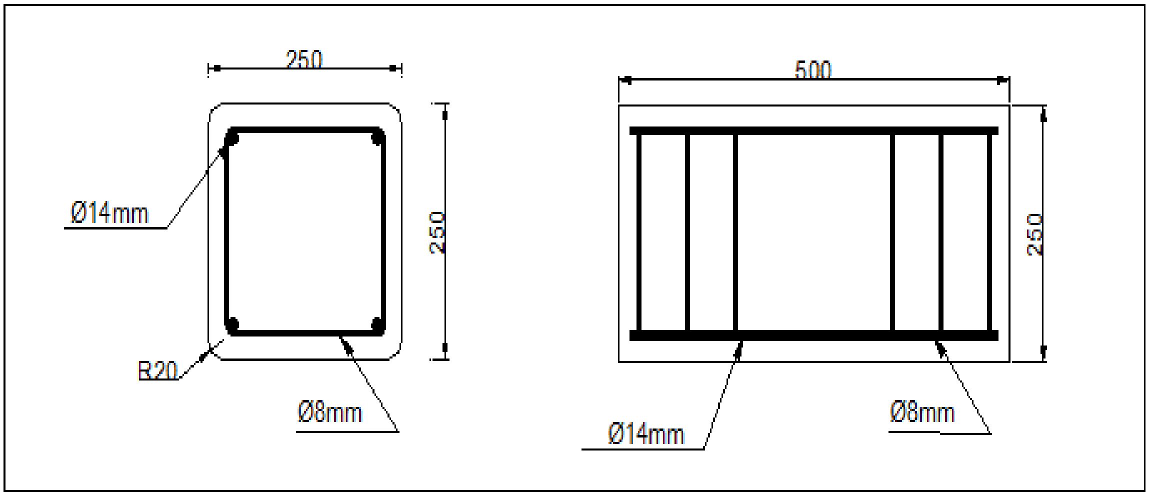


Figure (4.7):Geomertry

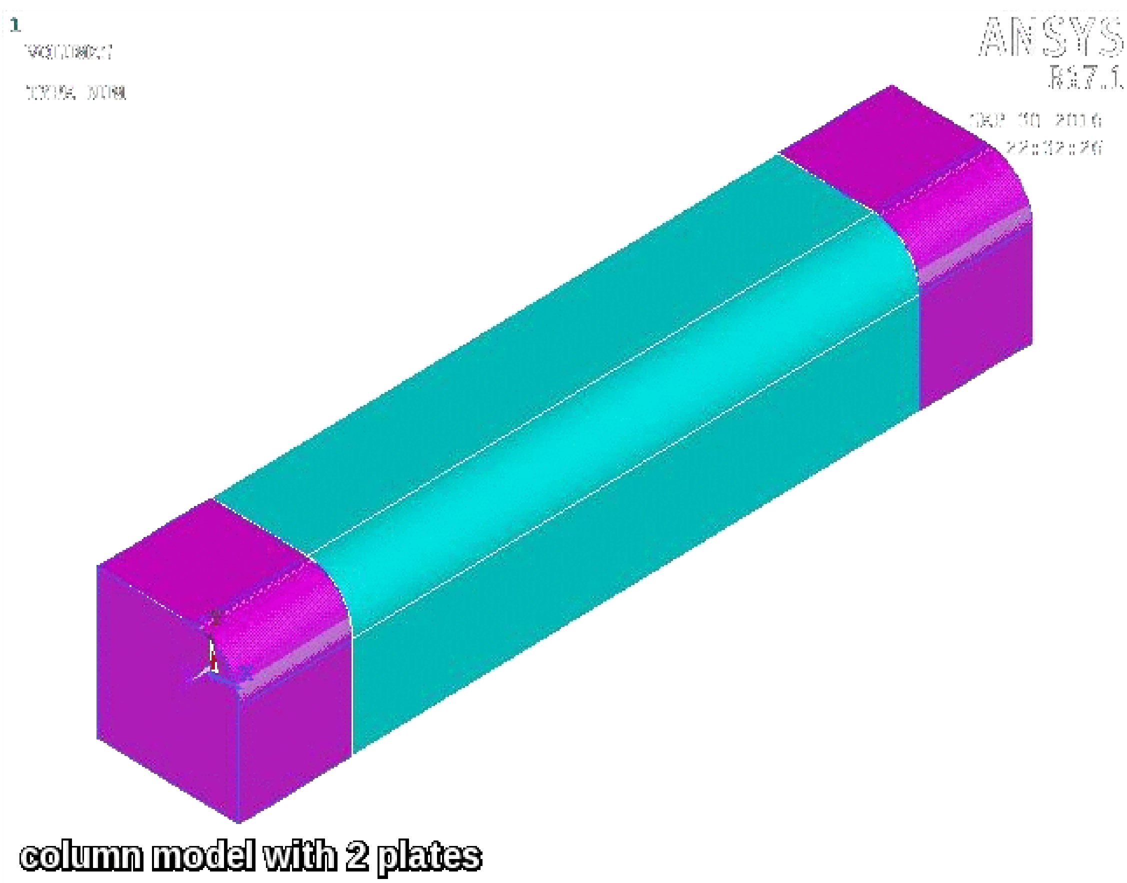


Figure (4.8): Volumes Created in ANSYS - column Model.

4.6 Meshing

Meshing of concrete , steel reinforcement , and FRP in Analyses model explain in the following section .

4.6.1 Concrete

To obtain good results from the Solid65 element, the use of a rectangular mesh is recommended (Wolanski, 2004; Kachlakev et al., 2001). Therefore, the mesh is set up such that square or rectangular elements are created. The overall mesh of the concrete column model is shown in Figure (4-9)

4.6.2 Reinforcement

Ideally, the bond strength between the concrete and steel reinforcement should be considered. However, in this study, perfect bond between materials was assumed.

To provide the perfect bond, the link element for the steel reinforcing was connected between nodes of each adjacent concrete solid element, so the two materials shared the same nodes, (Wolanski, 2004; Kachlakev et al., 2001).

The meshing of the reinforcement is a special case compared to the concrete volumes. No mesh of the reinforcement is needed because individual elements are created in the modeling through the nodes created by the mesh of the concrete volumes.

However, the necessary mesh attributes need to be set before each section of the reinforcement is created.

4.6.3 CFRP Fabric Layer

CFRP sheets were meshed as shell elements as shown in figure (4-10) in such a way that its nodes were oriented with adjacent concrete solid elements in order to satisfy the perfect bond assumption. The command ″merge items″ was used to merge separate nodes that have the same location.

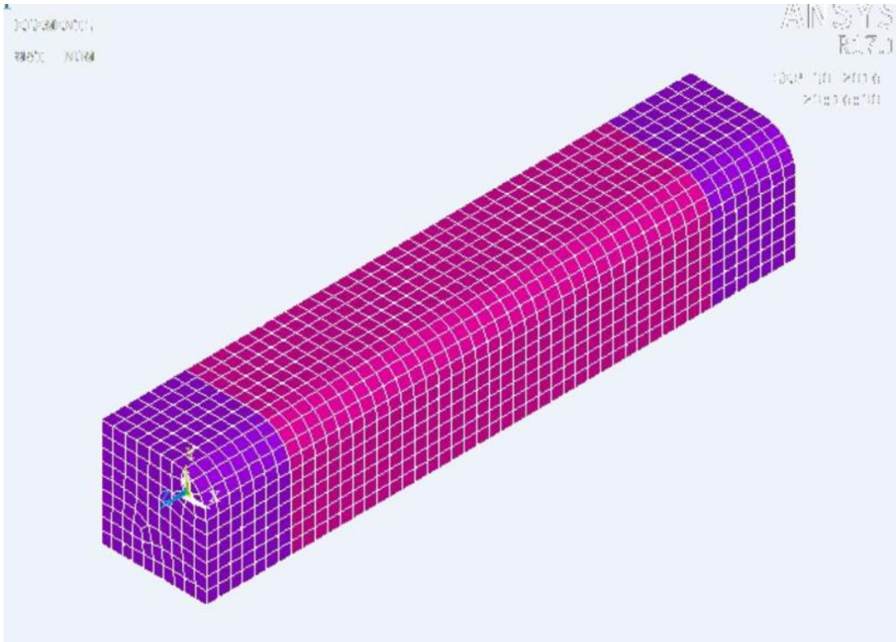


Figure (4.9): Mesh of the Concrete and Steel Plates – column Model

4.7 Loads and Boundary Conditions

Displacement boundary conditions are needed to constrain the model to get a unique solution. To ensure that the model acts the same way as the experimental column ; boundary conditions need to be applied at points of symmetry, and where the supports and loadings exist.

Because quarter of entire column was used for the models, the models being used are symmetric about one plane. To model the symmetry, nodes on this plane must be constrained in the perpendicular direction. Therefore, these nodes have a degree of freedom constraint UZ = 0, as shown in figure (4-11).

4.8 Setting Nonlinear Solution Parameters

Setting solution parameters involves defining the analysis type and common analysis options for an analysis, as well as specifying load step options for it. To ignore large deformation effects such as large deflection, large rotation, and large strain; the analysis option was set to (Small Displacement Static).

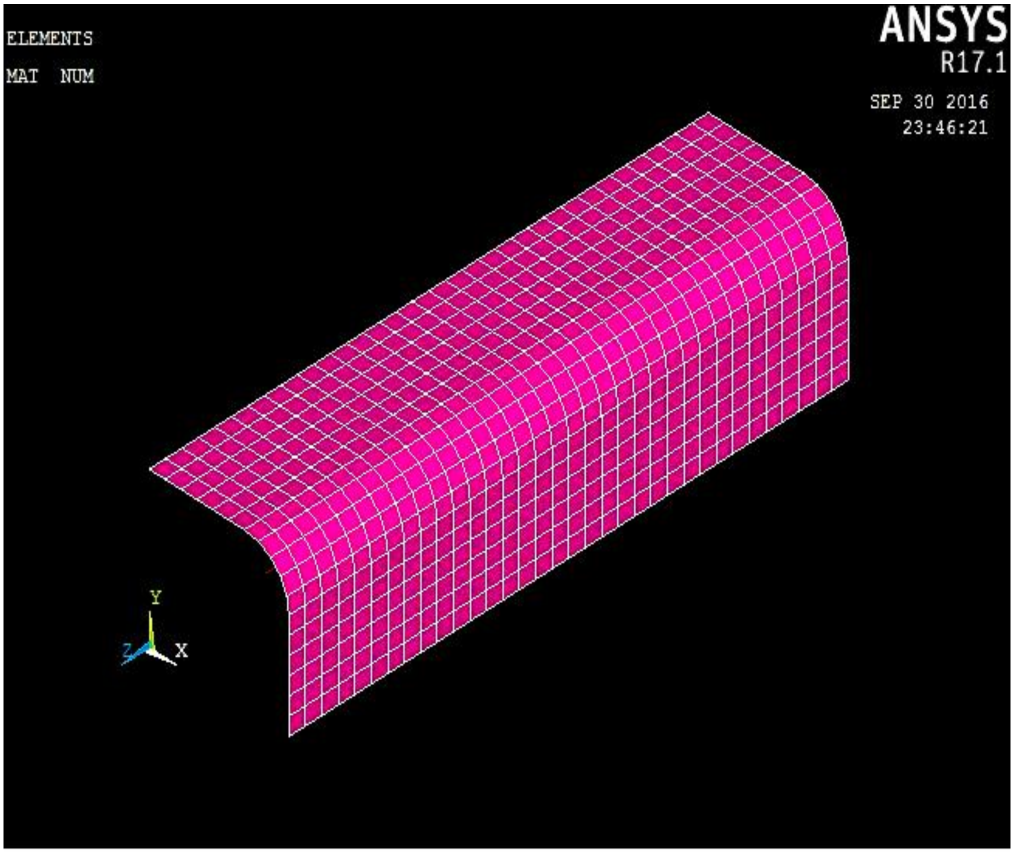


Figure (4.10): Meshing of CFRP Layer in ANSYS – column Model

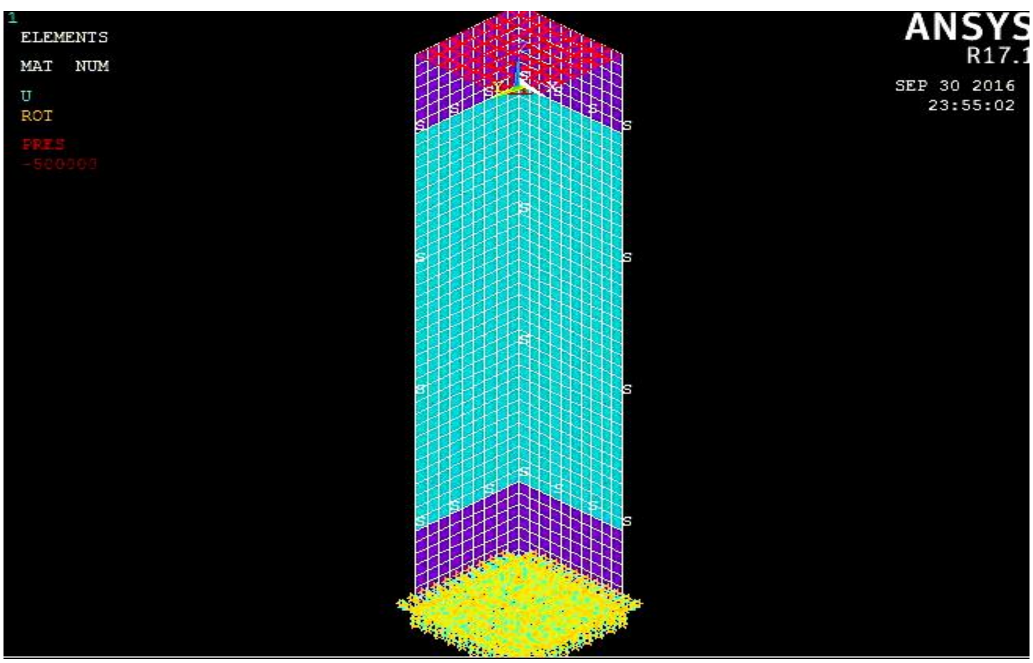


Figure (4.11): Plane of Symmetry – column Model

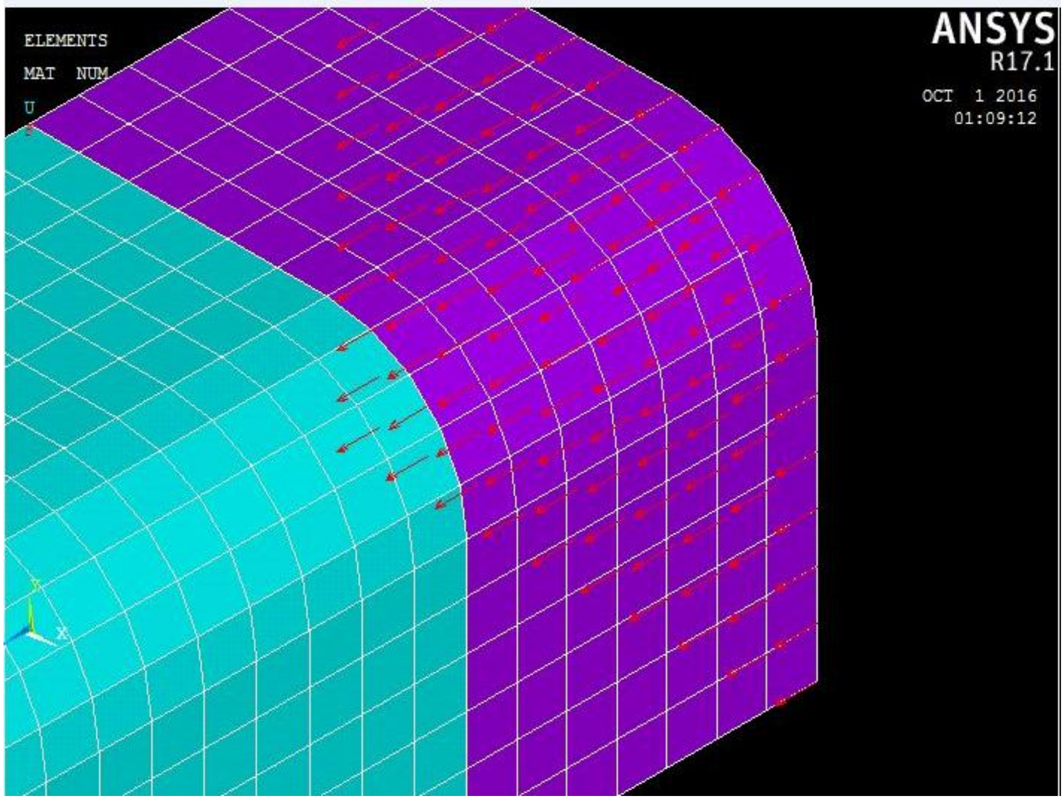


Figure (4.12): Loading Plate – column Model

4.8.1 Applied Loads

The force, P, applied at the steel plate is applied across the entire centerline of the loading plate, as shown in figures (4-12) .

In nonlinear analysis, the load applied to the structures must be increased gradually to avoid non-convergence. The total load applied to a finite element model is divided into a series of load increments called load steps. At the completion of each incremental solution, the stiffness matrix of the model is adjusted to reflect nonlinear changes in structural stiffness before proceeding to the next load increment, (ANSYS Mechanical APDL Manual Set, 2014). The ANSYS program uses Newton– Raphson equilibrium iterations for updating the model stiffness.

Automatic time stepping in the ANSYS program predicts and controls load step sizes. Based on the previous solution history and the physics of the models, if the convergence behavior is smooth, automatic time stepping will increase the load increment up to a selected maximum load step size. If the convergence behavior is abrupt, automatic time stepping will bisect the load increment until it is equal to a selected minimum load step size. The maximum and minimum load step sizes are required for the automatic time stepping, (ANSYS Mechanical APDL Manual Set, 2014).

Nonlinear static snalysis type was utilized for columns models. Typical commands utilized in the analysis are shown in Table (4-6).

Table (4.6):Nonlinear Analysis Control Commands in ansys

Analysis Options	Small Displacement Static
Calculate Prestress Effects	No
Time at End of Load Step	1
Automatic Time Stepping	On
Time Step Size	0.05
Minimum Time Step	0.001
Maximum Time Step	0.05
Write Items to Results File	All Solution Items
Frequency	Write Every Sub Step

The commands used to control the solver and outputs are shown in Table (4-7).

Table (4.7):Output Control Commands.

Equation Solvers	Sparse Direct
Number of Restart Files	1
Frequency	Write Every Sub Step

The commands used for the nonlinear algorithm and convergence criteria are shown in Table (4-8). All values for the nonlinear algorithm are set to defaults.

Table (4-9) shows the command used for the advanced nonlinear settings. ANSYS program behavior upon non-convergence for this analysis was set such that the program will terminate but not exit. The rest of the commands were set to defaults

Table (4.8): Nonlinear Algorithm and Convergence Criteria Parameters.

Line Search	On	
DOF solution predictor	Program Chosen	
Maximum number of	100	
Cutback control	Cutback according to predicted number of iter.	
Equiv. Plastic Strain	0.15	
Explicit Creep ratio	0.1	
Implicit Creep ratio	0	
Incremental displacement	1,00,00,000	
Points per cycle	13	
Set Convergence Criteria		
Label	F	U
Ref. Value	Calculated	Calculated
Tolerance	0.005	0.05
Norm	L2	L2
Min. Ref.	Not applicable	Not applicable

Table (4.9): Advanced Nonlinear Control Settings

Program Behavior Upon Non-convergence	Terminate but do not exit
Nodal DOF Sol'n	0
Cumulative Iterations	0
Elapsed time	0
CPU time	0

CHAPTER 5
Results and discussion

CHAPTER 5

Results and discussion

5.1 Introduction

In this chapter, comparison FE results with experimental data are presented and discussion the parametric study of the Effect of wrap thickness and Effect of fiber orientation .

5.2 Validation (comparison FE results with experimental data)

The validation of the FE analysis of the FRP-wrapped RC columns was checked with an experimental study reported. specimens of A-3 (square) was selected for the validation of the FE models. These specimen was the same as A-3 in our FE models, respectively. Fig.5.1 shows a comparison between the stress-strain response of the control specimens obtained from the tests and that resulted from the FE analysis (Mohammad, Farshid, & Amir, 2010).

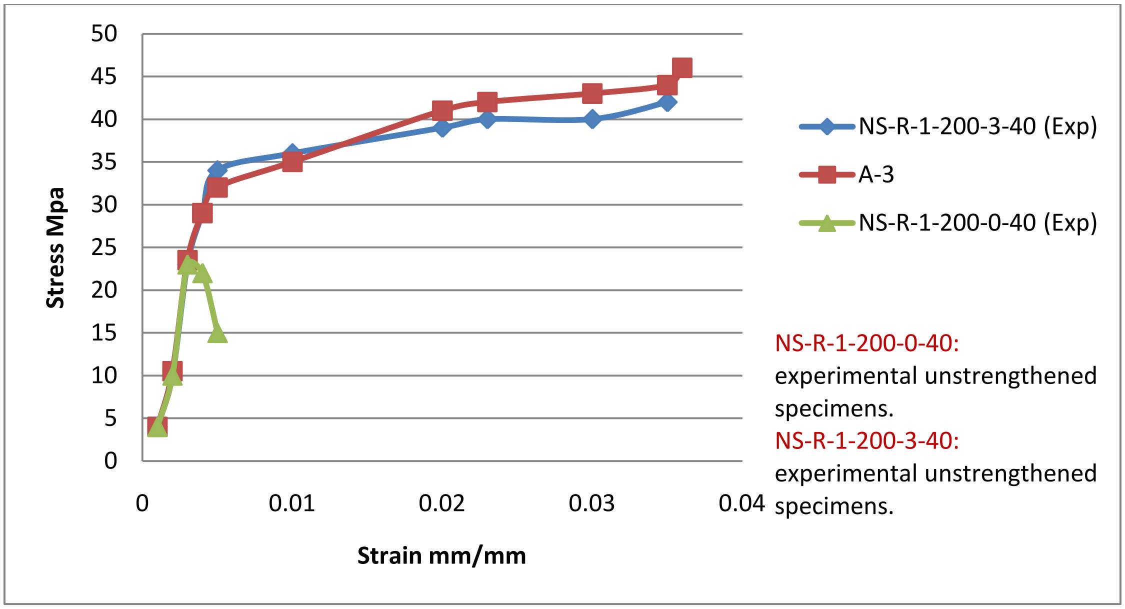


Figure (5.1): Comparison of the stress-strain of the finite element modelling and experimental tests

For better understanding of the FRP jacket effect on the behavior of the strengthened columns, the stress-strain responses of unstrengthened specimens (NS-R-1-200-0-40) are also shown in Fig. 5.1. In addition, the comparison of the finite element analysis (FEA) and the experimental results are presented in Table 5.1; in which f'_{cc} and ε_{ccu} are the maximum compressive stress and strain of the strengthened columns, respectively. It can be seen that the FE analysis results are very close to the test results. This means that the FE model is valid for predicting the behaviour of specimens and can be used to conduct a parametric study.

Table (5.1): Comparison of the finite element modeling and experimental data

Specimens		A-3	
f'_{cc}	Exp	41.85 Mpa	4.6%
	FE	43.84 Mpa	
ε_{ccu}	Exp	0.0331 mm/mm	3.0%
	FE	0.0341 mm/mm	

5.3 Parametric study

This section discuss the effect of warp thickness and the orientation of FRP comparing with the model results that have been done on A-3 .

5.3.1 Effect of wrap thickness

In this section, the effects of various wrap thicknesses on the behavior of the FRP-wrapped RC columns are investigated. To assess the confinement effect on the ductility of the specimens, the ductility ratios of all of the specimens were calculated. Ductility can be assessed by the ductility ratio (Mohammad, Farshid, & Amir, 2010), μ, which is defined by:

$$\mu = \frac{\textbf{Ultimate displacement}}{\textbf{Elastic displacement}} \qquad (5\text{-}1)$$

The ultimate displacement is defined as the point at which the load drops 20% from the peak load. The yield displacement is the yield point of an equivalent bi-linear response curve that provides an equal area to that of the response curve, as shown in Fig. 5.2.

For specimens without a post-peak behaviour and for which the column failed at the peak point, the last point is used for the ultimate displacement Fig. 5.3 and show the stress-strain response of

FE analysis results for the RC columns with three different wrap layers (one, three, and five). It is observed significant enhancement in the compressive strength and ductility of the columns compared to unstrengthened columns. With increasing of the number of layers, lateral confining pressure is increased. The increasing of the confining pressure causes that the concrete columns exhibit more axial stress and strain. Therefore, the columns with five layers exhibit the highest axial stress carrying capacity and axial strain compared to other columns (Mohammad, Farshid, & Amir, 2010).

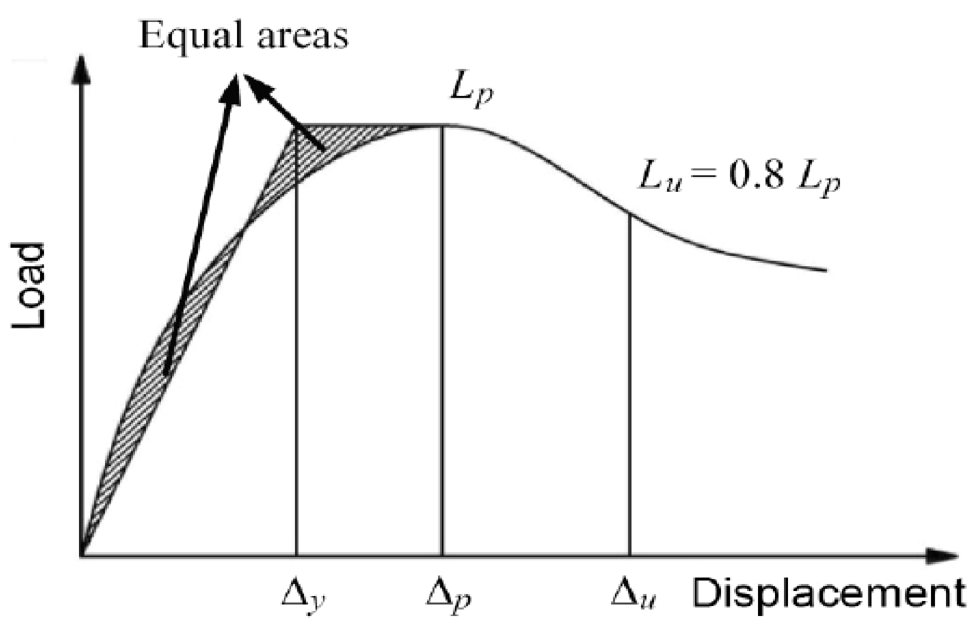


Figure (5.2): Definition of ductility ratio

The ductility ratios of the specimens are provided in Table 5.1; also the increasing proportions of ductility ratio (strengthened specimens to unstrengthened specimens) are provided in it. According to the Figs (5-3) , the mean of load carrying capacities of columns were increased 94%. Also according to the Table 5.2 , the mean of ductility ratios of specimens are 7 and 8 times of ductility ratios of unstrengthened specimens, respectively. As it was mentioned, concrete is non-uniformly strengthened. In Figs 5.4 the contours of compressive stress of concrete at mid-height of the square columns are shown. As it can be seen, the stress distribution over these sections is non-uniform and the level of non-uniformity is increased with the increasing of the number of layers (Mohammad, Farshid, & Amir, 2010).

Table (5.2):Ductility ratios

DUCTILITY	Unstrengthened Ductility ratio (mm/mm)	Strengthened Ductility ratio (mm/mm)		Proportion $\frac{\text{Strengthened } \mu}{\text{unstrengthened } \mu}$
Square columns	1.8	A-1	6	3.33
		A-3	13.4	7.44
		A-5	22.2	12.34

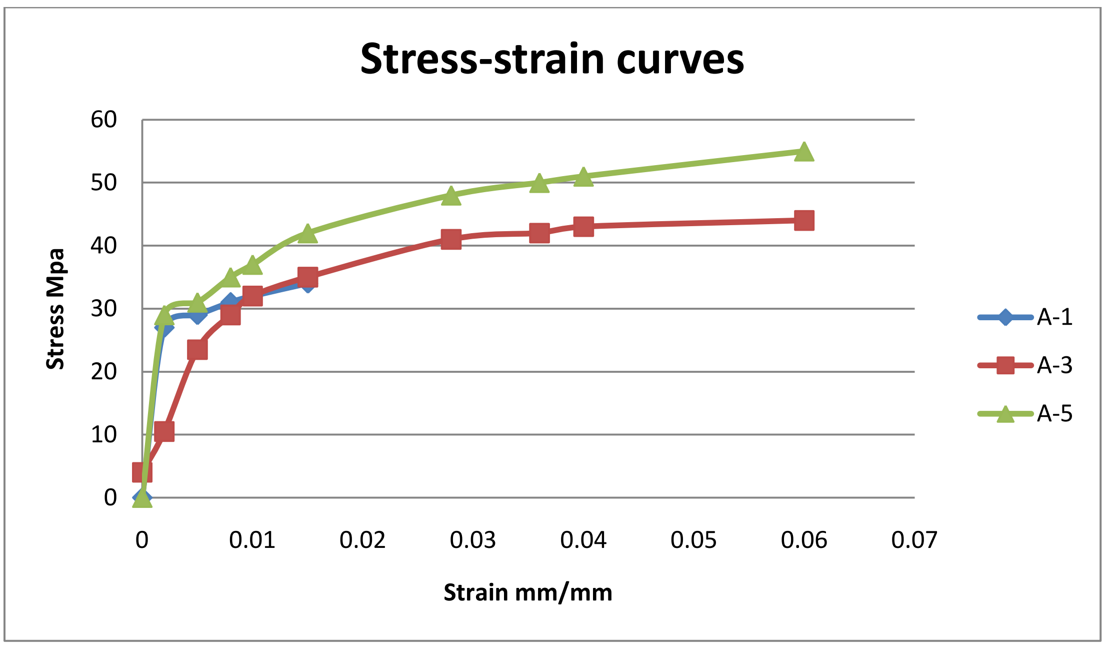


Figure (5.3): Stress-strain curves of square RC columns

This phenomenon is caused by the shape of the cross section. In fact, at any location of the cross section different lateral pressure from FRP wrap is applied and therefore, the distribution of compressive stress becomes non-uniform. In all models, the maximum axial compressive stress occurs in the neighborhood of the corners and its minimum happens at the middle of the larger sides. Also it is evident that the square specimens in comparison with rectangular specimens have more effective area of cross section in carrying higher compressive stress (see Figs 4 and 5) that leads to the square specimens have more axial load carrying capacities in comparison with the rectangular specimens. In Fig. 5.4 contour of strain for FRP jacket in hoop direction for specimen R–3 is shown. All column models wrapped with one, three, or five layers of FRP failed due to the rupture of FRP at near mid-height of the columns. Intensive stress concentration occurred at the corners where contact between concrete and FRP was the highest. This high outward contact force produced tensile strains in the FRP wrap in hoop direction (Mohammad, Farshid, & Amir, 2010).

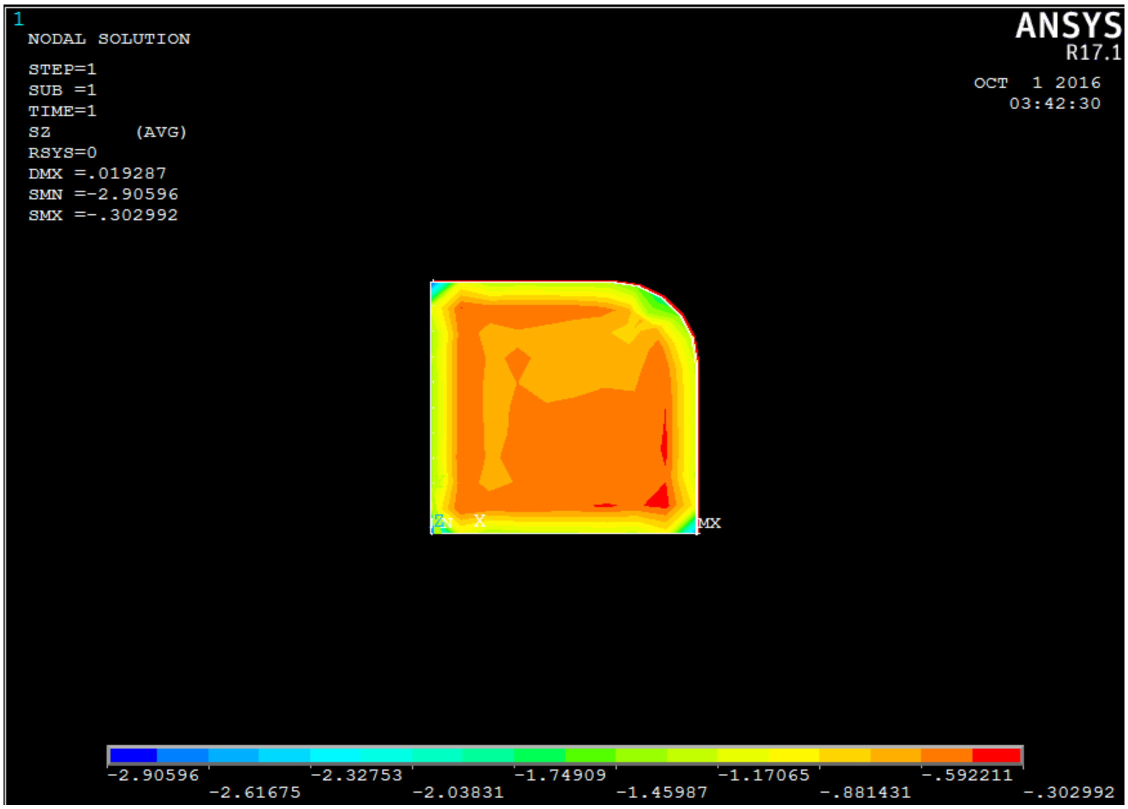


Figure (5.4): Contours of axial compressive stress of concrete at mid-height of square columns

5.3.2 Effect of fiber orientation

In this section, the effect of fiber orientation of FRP jacket on the stress-strain response of specimens A-3is considered. The fiber orientation 0°, ±15°, ±30°, and ±45° with respect to horizon were considered. Fig (5-6) show the effect of the fiber orientation on the stress-strain response of specimens A-3. Table 5.3 shows ductility ratios of the specimens A-3versus the fiber orientation of the wrap. It was observed that the fiber orientation of wrap strongly affects the stress-strain response of the specimens (Mohammad, Farshid, & Amir, 2010).

The hoop orientation of fibers (0°) results in the largest gain in ultimate stress, while the fiber orientation of ±45° leads to the largest ultimate strain. The specimen shows lower decreasing of axial load-carrying capacity in comparison with specimen A-3 however, they are not much different in increasing of axial strain and ductility (Mohammad, Farshid, & Amir, 2010).

When the fiber-wrapped concrete is subjected to an axial compression loading, due to bonding between concrete core and FRP jacket, FRP is deformed. In this case, considering the fiber orientation of wrap more than 0°. the deformation causes the compression deformation of the fibers and leading FRP wrap fail with more lateral expanding concrete core. This phenomenon causes increasing the axial strain of specimens . However, fiber orientation (more than 0°) leads to the applying less confining pressure to concrete core and concrete specimens exhibit less axial stress. The increasing of the fiber orientation causes that the concrete specimens exhibit more axial strain and less axial stress (Mohammad, Farshid, & Amir, 2010).

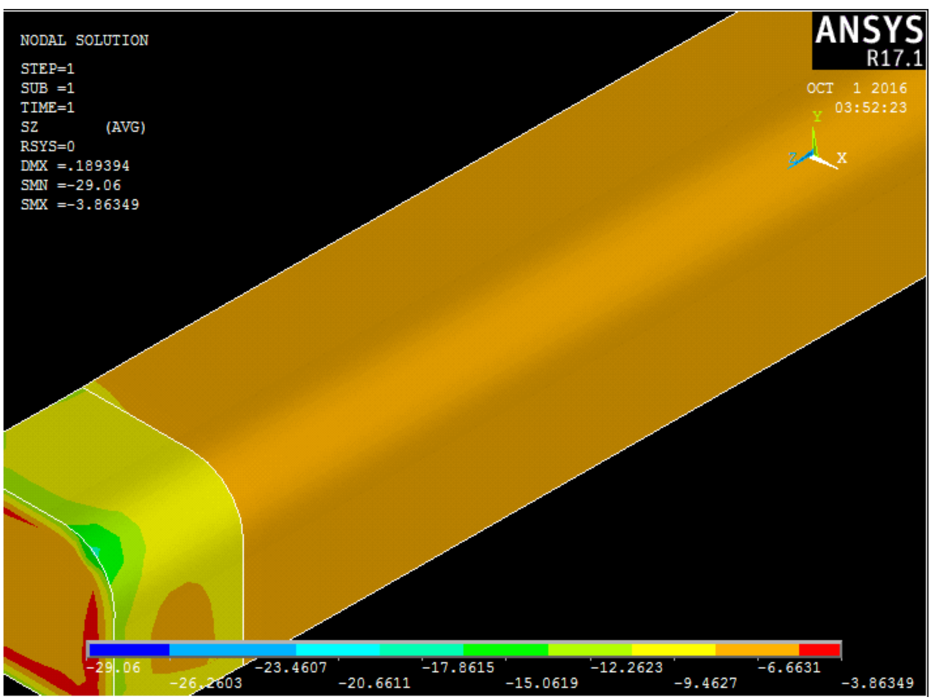


Figure (5.5):FRP tensile strain distribution in specimen A–3

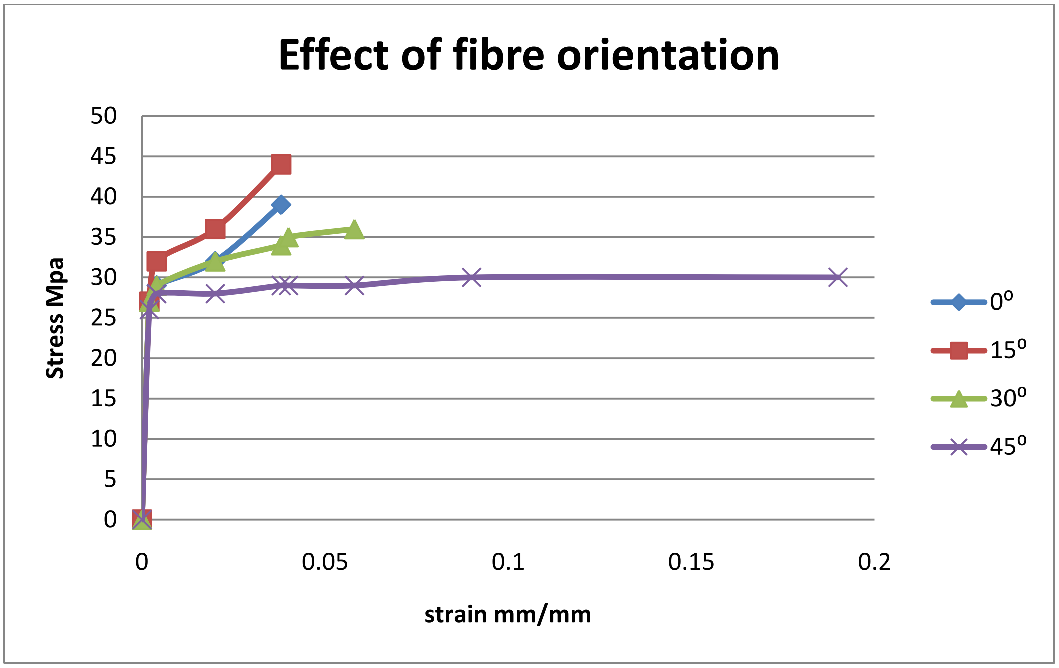


Figure (5.6):Effect of fiber orientation

Table (5.3):Effect of fiber orientation

Specimens	Fiber orientation			
	±0°	±15°	±30°	±45°
A-3 (μ mm/mm)	13.4	12.9	20.5	44.2

CHAPTER 6
CONCLUSIONS AND RECOMMENDATIONS

CHAPTER 6
CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusions

The important conclusions drawn from the study are listed below:

1. The finite element analysis results showed substantial increase in the axial compressive strength and ductility of the FRP-wrapped RC columns compared with the unstrengthened columns.
2. Strengthening the RC column by bonding a single layer of CFRP to the tension face of the column increases strength of the column by 20%.
3. Increasing number of CFRP layers bonded to the column soffit increases the stiffness of the column , increases its ultimate capacity.
4. Strengthening the RC column by bonding two layers of CFRP to faces of the column increases the strength of the column by 25%.
5. Strengthening the RC column by bonding three layers of CFRP fabric to faces of the column increases the strength of the column by 32%.
6. The gain in axial compressive strength was observed to be the highest in the columns wrapped with the hoop orientation; but the highest axial strain and ductility were observed in the columns wrapped with the fiber orientation of ±45° with respect to the horizon.
7. The wrap thickness has a significant effect on the strength and ductility of the columns. Increasing the wrap thickness increases the strength and ductility of columns, considerably. Increasing of axial load-carrying capacity of the square specimens is significantly higher than that for rectangular specimens.

6.2 Recommendations

1. In this study, the commercial Finite Element analysis software (ANSYS) was used in the analysis process. Comparative studies using other available Finite Element softwares can be conducted to investigate which one can give more precise results comparing with experimental investigations.

2. In this study, the external strengthening of RC column with CFRP was investigated. Strengthening with other available Fiber Reinforced Polymer (FRP) materials like Glass Fiber Reinforced Polymer (GFRP) can be studied to investigate the efficiency of the strengthening technique using different materials with different properties.

3. In this study, the bond between concrete and CFRP fabric was assumed to be perfect. Although this assumption did not cause a significant error in the obtained results comparing with experimental investigations; the behavior of the concrete-CFRP bond and de-bonding issues can be studied analytically to get more precise results especially regarding failure modes.

4. In this study, the influence of some parameters on the overall response of the strengthened RC columns has been investigated. These parameters are: effect of number of CFRP layers, effect of CFRP length, and effect of CFRP inclination. Effect of other parameters as column stiffness, column geometry, CFRP stiffness, and CFRP width on the behavior of the strengthened RC columns can be also studied.

The Reference List

The Reference List

ACI 440R-07. (2007). *Report on Fiber-Reinforced Polymer (FRP) Reinforcement for Concrete Structures.*

ANSYS Mechanical APDL Manual Set. (2014). *Release 14.5.* Southpointe: ANSYS Inc.

ASTM A615. (1995). *Standard specification for deformed and plain billet steel bars for concrete reinforcing.* Newyourk: American society for testing and material.

Athanasios, I., Theodoros, C., & Georgia, E. (2007, July 16-18). Three-dimensional finite element analysis of reinforced concrete columns strengthened by fiber reinforced polymer sheets. *Laboratory of Reinforced Concrete* , pp. 1-10.

Barbato, M., & Hu,D. (2014). Simple and efficient finite element modeling of reinforced concrete columns confined with fiber-reinforced polymers. *Engineering Structures , 72*, 113–122.

Basappa, U., & Rajagopa, A. (2013). Modeling of CFRP Strengthened RCC Beam Using the Nonlinear Finite Element Method. *Journal of Structural Engineering , 40* (23), 169-184.

Chansawa, K., Potisuk, T., Miller, T., Yim, S., & Kachlakev, D. (2009). E Models of GFRP and CFRP Strengthening of Reinforced Concrete beams. *Advances in Civil Engineering , 2009* (2009), 13.

Hajsadeg, M., & Alaee, F. J. (2010). Numerical analysis of rectangular reinforced concrete columns confined with FRP jacket under eccentric loading. *Advances in FRP Composites in Civil Engineering* , 658-661.

ISIS. (2006). *An Introduction to FRP Composites for Construction.* Canada: ISIS Educational Module.

Jijin, V., & Preetha, P. (2012). Comparative study on GFRP jacketed rc columns and CFRP jacketed rc columns of different shapes. International Journal of Engineering Research and General Science. *International Journal of Engineering Research and General Science , 3* (7), 475-488.

Julien, M., & Emmanuel, F. (2015). *experimental study on rc columns retrofitted by frp and subjected to seismic loading.* Paris: Université Paris Est.

Kotsovos, D. M., & Pavlovic, M. N. (1995). *Finite-element analysis for limit-state design.* Wiltshire: Thomas Telford.

Martin, A. M. (2013). *Introduction of Fiber-Reinforced Polymers − Polymers and Composites: Concepts, Properties and Processes.* london: ISBN.

Mohammad, H. (2015). Non-linear Finite Element Analysis of Reinforced. gaza, Palestine, Palestine: The Islamic University of gaza.

Mohammad, H., Farshid, J. A., & Amir, S. (2010). Investigation on behaviour of square/rectangular reinforced concrete columns retrofitted with frp jacket. *Journal of Civil Engineering & Management , 17* (3), p400-408.

Mohammed, A. (2015). Nonlinear Finite Element Analysis of RC Beams Strengthened with Steel Fiber-Reinforced Concrete (SFRC) overlays. gaza, Palestine, Palestine: Islamic university of gaza.

Neale, K., Ebead, U., Abdel Baky, H., Elsayed, W., & Godat, A. (2005). Modeling of Debonding Phenomena in FRP-Strengthened Concrete Beams and Slabs. *Proceedings of the International Symposium on Bond Behavior of FRP* .

Potyrała, P. (2011). *Use of Fiber Reinforced Polymer Composites in Bridge Construction. State of the Art in Hybrid and All-Composite.* catlonia: Construcció.

Prabhakaran, P. (2015). comparative study on GFRP jacketed rc columns and CFRP jacketed rc columns of different shapes. *International Journal of Engineering Research and General Science* .

Rasmussen, A. B. (2012). *analytical and numerical midel of reinforced concrete in servicability limit stat.* Aarhus: AARHUS UNIVERSITY.

Rots, J. G., & Blaauwendraad, J. (1989). *Crack Models for Concrete.* Delft: HERON.

Saravanan, J. (2014). Experimental Study on RC Columns Wrapped With Hybrid FRP Sheets. *Journal of Structural Engineering* , 1-15.

Setunge. (2002). *Review of strengthening techniques using externally bonded FRP composites.* CRC.

Tavio, T., & Tata, A. (2009). Predicting Nonlinear Behavior and Stress-Strain Relationship of Rectangular Confined Reinforced Concrete Columns with ANSYS.

Teng, J., Chen, F., Smith, S. T., & Lam, L. (2001). *FRP: Strengthened RC Structures.* london: WileyCDA.