Structural Retrofit of Reinforced Concrete Circular Columns using CFRP

By

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Abstract

Fiber reinforced polymer (FRP) composites have developed numerous applications in the field of Civil Engineering, mostly because of their beneficial properties like high strength-to=weight ratio and high corrosion resistance. This study presents an easy and expedient finite element (FE) able to accurately estimate the axial load carrying capacity of reinforced concrete (RC) circular columns confined with externally bonded carbon fiber reinforced polymer (CFRP) sheets. The element is able to model collapse due to concrete crushing.

The FE generated in this study is used the load carrying capacity of CFRP confined RC columns subjected to concentric loading. Constitutive models for materials (concrete, steel, CFRP) present in the literature and made available by different authors were used to form numerical simulations. These simulations are compared with experimental results from tests conducted and ACI and NCHRP design guidelines. The present research work is both experimental and simulation. In this way the efficiency of CFRP wraps as strengthening material can be well corroborated by three means.

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Chapter 1

Introduction

1.1 Background

Considerable number of existing RC columns which were built in past do not meet current design needs in terms of strength. The need of rise in axial strength of concrete column comes into picture whenever repair and strengthening are involved. Repair may be needed whenever columns are damaged under excessive external loads or due to erosion in exposed environments. And whenever there is a change in structural use, removal of some adjacent load bearing structural elements to void the structural discontinuity, strengthening is needed. In such circumstances, the additional load bearing capacity of the existing columns can be provided by external confinements. The idea of increasing the strength in axial direction by providing lateral confinement was originally develop back in the 1920s' (Ching Au). There are various forms of this confinement. They are; spiral and circular reinforcements; concrete jacketing; steel jacketing; and fiber reinforced polymer (FRP) composite jacketing. Though steel is widely used as construction material, corrosion and weight are some inherent drawbacks in it, construction costs increase when installation is labor intensive. On the similar lines, concrete jacketing simply adds weight and cross sectional area to original structure, though has a lower cost, may be undesirable.

In the recent research studies by structural engineers, they have been researching substitutes to steel confinement in order to reduce the high costs of repair and maintenance of damaged or inadequate structures. In the retrofit of structural systems, composite materials which are formed by the combination of two or more distinct materials are at the microscopic sale, have gained widespread use. One of these materials, fiber reinforced polymer (FRP) are relatively new which were developed in the early 1940s for different type of applications in mechanical and aeronautical engineering. High-strength high-stiffness structural fibers combine with low cost polymers which are also resistive against adverse environmental effects to form composite materials with better mechanical properties than either of the constituents alone. By this, these materials can provide impeccable combination of properties at a lower cost compared to other structural materials. These can be used to significantly strengthen beams, columns and slabs with negligible increase in structural size and weight. These cease electrochemical corrosion and have demonstrated excellent durability in harsh environmental conditions. These usually weigh less than one fifth of weight of steel and their tensile strength can be as much as eight to ten times as high, by this it is evident that these have high strength to weight ratio. These materials find their use in construction industry because their mechanical properties.

To supplement the confining reinforcement provided by internal reinforcing steel, FRP sheets can be bonded to the exterior of concrete structures with high strength adhesives. By doing this, reduction of impact of other degradation processed due to adverse environmental conditions and enhancement of strength of concrete due to the confinement of FRP can be achieved.

Figure 1 Picture of two technicians wrapping bridge piers with FRP sheets (Dan Hu)

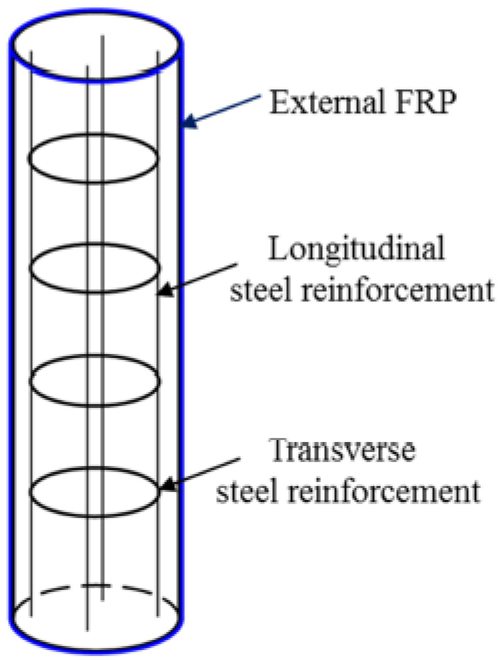

Figure 2 Typical sketch of a RC column confined with external FRP, which is typical example of structural members considered in this study (Dan Hu)

1.2 Objectives of this research

Strength, ductility and durability of RC members can be improved by retrofitting them with externally bonded FRP and it is widely recognized as an efficient way of doing so. This technique is also used to retrofit structures located in earthquake prone regions. It is critical for an analyst to properly understand and should be capable of accurately modeling the stress-strain behavior of FRP confined concrete for its reliable use, so as to predict the improved performance of it based on the specific geometry, material properties and mount of FRP utilized. Thus, numerous numerical tools have been developed to model the structural behavior of FRP-confined RC columns. Due to complexity of problem, attaining this feat of understanding and modeling the behavior of FRP-confined RC columns is still a very active field.

This study focuses on the estimation of axial strength of the externally bonded circular RC columns under uniaxial compression using ACI 440.2R-08, checking it with experimental testing of the same and finite element modeling. By this, the performance of CFRP wraps based on number of layers, orientation of wraps when applied can be accurately found out. Various constitutive models for materials are used to simulate the FE model on ABAQUS CAE.

1.3 Scope

The core of this research deals with the modeling of response of FRP-confined RC circular columns subjected to uniaxial compressive load, experimental testing of them for the same and checking the results with the code equations Cyclic loading which is more observed in earthquakes is beyond the scope of this study.

1.4 Organization of thesis

Chapter one states about the introduction of the experimental. Chapter two gives an overview of literature review and FRP material properties and previous research programs in the similar field. Chapter three is about the experimental program which explains about the test setup. Chapter four has the finite element model and the techniques used in it. Chapter five contain results obtained from FEA and design guidelines. At last, chapter six has discussions and conclusions.

Chapter 2

Literature review

2.1 Introduction

Fiber reinforced polymer (FRP) composites as discussed earlier were initially developed for aeronautical and mechanical applications, but since their material properties favored them to be used in construction industry, they are now widely used for new construction and repair of the old ones.

This chapter reviews these materials, their mechanical behaviors and their resistance to aggressive environmental conditions. The types of fiber reinforcements and resin matrices; the mechanical behaviors such as strength; environmental effects like weathering, corrosion and flammability; contemporary applications are discussed.

2.2 An Overview of FRP composite materials

FRP composites are composed of Fiber reinforcements embedded in resin matrix. The mechanical properties of composites are dominated by fiber reinforcements. The higher number of fibers in a composite results in higher strength of composite. On the other hand, low matrix to fiber ration give rise to premature failure or strength reduction. Not only density of fibers, but also the length and orientation of them play a critical role in defining strength.

Fibers in composite are prevented from buckling by resin matrix, it binds the fibers through cohesion and adhesive and thus protects fibers from attack and micro cracking during service; prevents delamination, lap joint de-bonding and impact damage by providing shearing strengths between layers.

Choice of a particular fiber and resin depend upon the factors like strength requirement, service life, environment conditions, ease of installation and cost. For instance, choice of composite for retrofitting of a group of interior columns may not be the same as the choice of composite for interior building columns. Thus, these factors have to be given considerable attention.

FRP composites are available in two types for column retrofit, continuous fiber strands and weaved fabric cloths. Former is used in the process of filament winding, using an automated system, which is a method which uses sight fiber pre-tensioning to produce column confinement. Later is the one which are wrapped on columns surfaces directly using techniques such as wet lay-up and vacuum hogging thus producing the confinement after they fully cured and hardened. For new construction of columns, pre-fabricated FRP composite shells are used as the concrete forms and later those shells will stay as it is on column as permanent confinement shells. Depending on actual design and construction requirements, these shells can come in different thickness, fiber content and dimensions.

2.2.1 Basic materials of FRP composites

Fiber reinforcements and resin matrix are two components FRP composite; glass, carbon and aramid re types of fibers are the most commonly used in construction industry due to their light weight, superior tensile strength and corrosion resistance. Figure compares the strength and stiffness of typical carbon fiber composite, glass fiber composite and construction steel.

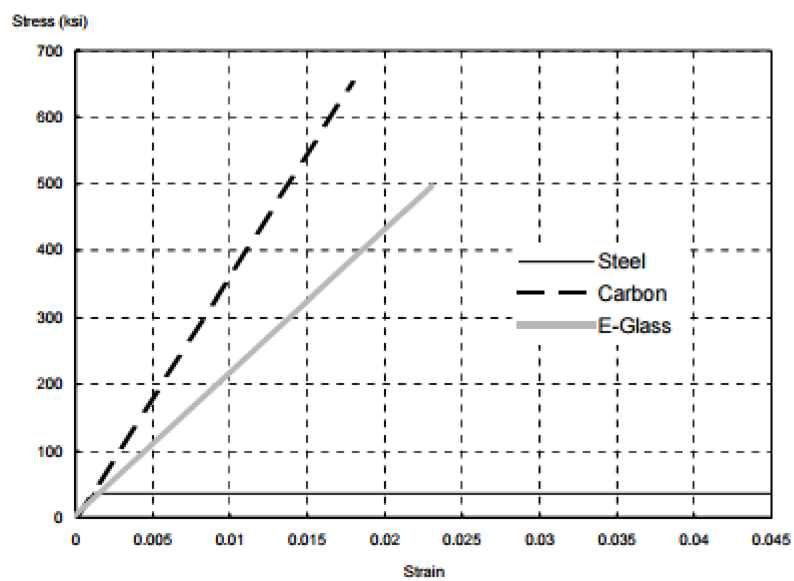

Figure 3 Comparison of strength and stiffness of A36 steel, carbon and glass fibers (Ching Au)

Acceptable resins are the ones with good adhesion capabilities, high toughness, excellent stability and curing properties. Epoxies and poly-esters are the ones which satisfy above criterions. In the subsequent section, the above mentioned fibers and resins are described.

2.2.1.1 Fiber Reinforcements

A. Glass Fibers

These are of two types, E glass and S glass, where in E stands for Electrical and S stands for Structural. Thus, E –glass possess excellent electrical insulation characteristics while S – glass has higher strength and greater corrosion resistance**.** These fibers are calcium aluminoborosilicate formulations, are inorganic and do not support combustion. E-glass fibers are considered to comply with industry standards since they are cost efficient, whereas S- glass fibers have higher strengths due to their higher alumina content. Typical filament strength and stiffness values are presented here

Table 2-1 Mechanical Properties of E-Glass and S-Glass Filaments (Ching Au)

Properties	E-Glass	S-Glass
Strength (GPa)	3.447	4.619
Stiffness (GPa)	72.39	85.49

The fiber surface of glass fibers is prone to moisture attack under certain exposure conditions and above certain stress levels. If proper remedy is not provided, this will lead to stress rupture.

B. Carbon Fibers

The main source for production of carbon fibers are organic precursor fibers such as rayon or polyacrylonitrile (PAN). Thermal decomposition of PAN followed by a stabilization and carbonization procedure. Other alternative precursors are coal, petroleum and synthetic pitches. The fabrication involves a spinning process. PAN based carbon fibers are predominant compared to pitch based because they have higher tensile strength. The stand out mechanical properties are elastic modulus, tensile modulus, thermal conductivity, electrical conductivity. The typical tensile strengths of carbon fibers are 600- 700 KSI which is equivalent to higher range values found in S- glass fiber strengths. Some even show strengths as high as 1000 KSI, which are less consumed in industry due to the obvious reason of being costly. Carbon fibers are more brittle than glass fibers but have unusual fatigue resistance; moreover, stiffness is higher than all metals.

C. Aramid Fibers

Aramid fibers are organic in nature which are polyamide formulation. They are two types of, para-aramid and meta-aramid fibers. Para-aramid fibers' commercial name is Kevlar fibers, they have higher strength and are usually used in high performance applications. These fibers are highly thermal resistive because the fibers themselves do not readily conduct heat into the matrix and due to their highly aromatic and ordered structure. They do not melt prior decomposition and the typical decomposition temperature is around 450 C. The tensile strength is about that of mid-range carbon fibers (typical 400 KSI) and stiffness is about 15x10pow6 psi. However, the major drawbacks are; they easily buckle or kink under compression forces and the fibers damage thus resulting in very low bending and compressive strengths, relatively low adhesion to most resin matrix materials, high moisture absorption by the fibers.

2.2.1.1.1 Forms of Fiber Reinforcements

Reinforcing fibers appear in various forms, depending on the application. Each form is elaborated below.

A. Staples

Staples are used to produce reinforcing mats or surface mats. They are used to reinforce concrete mix by direct addition of chopped fibers with concrete during mixing. They enhance the load carrying capabilities because they take stresses in their direction and prevent cracks in the matrix or concrete from developing and propagating. Due to the random orientation of the short fibers (length less than 0.02”), they exhibit isotropic properties.

B. Continuous strands

These are used in column winding and are made of many single fiber filaments twisted together or made of several untwisted strands adhered together by means of chemicals. These strands do not have any stress concentrations which occur when stretched under tension. Hence, they have higher strengths compared to woven fabrics. They act as the basic unit of woven fabrics.

C. Fabric Cloths and Tapes

Fabric cloths are produced from continuous strands. They are weaved in patterns like textile cloths. Depending upon the application and design requirements, these cloths are weaved using continuous fiber strands with specific fiber content. During weaving when the fabric is stretched under tensile pull, kinking at cross points occur, points of stress concentration forms which eventually damage the epoxy bonding and form white dots, demonstrating locally high stressed resin and relative movements of the fiber roving in orthogonal directions. This also leads to lower tensile strength. Fiber cloths are trimmed to size to form fiber tapes. Woven roving has higher load capacities than that of fabric cloths. They differ to fiber cloths in a way that it they are made of thicker fiber roving than the twisted fiber strands.

2.2.1.1.2 Comparison of Cost and Thickness

Extra fabrication processes usually lead to increase in cost, here the cloth fabrics and woven roving need extra fabrication process and one more level of quality control, the fabric weaving process. Thus cost of fiber strands for filament winding is the lowest. Table shows the cost ratios and size ranges of respective forms of fiber reinforcement.

Table 2-2 Comparison of cost and thickness of various forms of Fiber Reinforcements (Ching Au)B

Properties	Continuous Strands	Fabric Cloths	Woven Roving
Cost factor (per lb)	1- 2.5	3.5-6.5	2-3.5
Thickness (inch)	0.0026”-0.055”	0.0010”-0.045”	0.027”-0.048”

2.2.1.2 Resin Matrix

A. Epoxy Resins

Epoxy resins are the ones which are predominantly used to form composites which are used for civil structures. This feat is achieved by these resins because of the impeccable mechanical properties they exhibit. For instance, They provide excellent adhesion to a wide variety of fibers because of their inherent polar nature; they have a low level of shrinkage upon curing, there is no release of volatile by-product that causes bubbles void formation in the curing process; epoxy has a very high toughness due to their crosslinked structure. But there are some drawbacks of this material; they have a tendency to absorb the moisture both in cured or uncured stage, also the elongation to failure is relatively low. Thus, there were improvements which addressed the elongation issue by using modified resin formulations. It was reported that no degradation of the composite materials has been observed even after over 20 years of service exposure (Ching Au). Curing at room temperature and heat accelerated curing are available (Ching Au).

B. Polyester Resins

Liquid polymers can be stored for months and are very stable at ambient temperatures, peroxide catalyst can be used to accelerate curing. These polyester undergo thermosetting process which consists of a chemical reaction that cross-links the material to form polymer and this process is irreversible. These resins are best suited for glass fibers, when used with carbon or aramid fibers, adhesion and cure shrinkage are a problem. Since, carbon and aramid are widely used in construction, there is a decline in the use of these kind of resins.

2.2.2 Mechanical Behaviors of FRP Laminates

FRP laminates are one of major materials in this study, their mechanical properties which are to be discussed here include stress-strain relationships, effect of orientation, creep, resistances to fatigue and impact. Isotropic and orthotropic laminates are discussed here.

2.2.2.1 Stress-strain relationship

Stress and strain behaviors can be analyzed through two views, microscopic and macroscopic. The former view considers fiber and matrix as two distinct entities while the latter view considers them to be a single homogeneous entity but allowing the directional properties. The equations in the subsequent sections that present both micro- and macro-mechanics are taken from the work of Ching Au.

2.2.2.2 Micro-mechanics Representations

A. Isotropic Laminates

These type have fibers oriented in many directions thus it has directionless properties and hence treated as isotropic. Interfacial de-bonding and crack propagation are micro behaviors, the isotropic property of fibers make the crack propagation prediction very complex and hence macro behaviors are preferred when dealing with isotropic laminates.

B. Orthotropic Laminates

Clearly defined bonding interface can be identified due to presence of long continuous fibers in the matrix. Though, fibers and matrix behave quite similarly under the application of external loads and they have considerable interaction between them, they are considered separate entities in this analysis. The mechanical properties like elastic moduli and stresses are considered separately but their effects are superimposed to find the resultant for the composite material.

Consider a simple case where laminate consists a unidirectional fibers which are aligned along a load vector. For a given tension, the following equation applies.

$$F = \sigma * A = \sigma_f * A_f + \sigma_m * A_m$$

Where,

F= applied force,

Sigma = mean stress on entire cross-section

A = total cross-sectional area

σ_f = stress in fiber

A_f = cross sectional area of fiber

σ_m = stress in resin matrix

A_m =cross sectional area of resin matrix

In this case perfect bonding is assumed, so to satisfy the compatibility equation which means that two entities should move together. Therefore, the equation,

$$\frac{\sigma_m}{\sigma_f} = \frac{E_m}{E_f}$$

Where,

E_m = Elastic modulus of resin matrix

E_f = Elastic modulus of fiber

Moreover, in longitudinal direction the elastic modulus of the composite is given by

$$E * A = E_f * A_f + E_m * A_m$$

The above defined parameters are applicable here. Volumetric ratio is directly proportional to the cross sectional area, so they can be substituted for each other. In first and third equations, the cross sectional areas can be entirely substituted b the corresponding volumetric ratios V_f and V_m. If these ratios are used the total cross sectional area can be substituted by unity, which is the sum of fibers and matrix volumetric ratios.

2.2.2.3 Macro-mechanics Representations

A. Isotropic Laminate

In these laminates, the elastic modulus is identical in all directions, the mechanical properties follow the Hooke's law such as in stress-strain behavior and the Poisson's ratio v is related shear modulus G and Elastic modulus E like in the subsequent equation,

$$G = \frac{E}{2(1 + \nu)}$$

Similarly, stress (σ), strain (ε), shear stress (τ) and shear strain (γ) are related as follow

$$\varepsilon = \frac{\sigma}{E}$$

$$\gamma = \frac{\tau}{G}$$

B. Orthotropic Laminate

Fabric cloths and weaved roving have different Elastic Moduli and Poisson's ratio in different directions since they are orthotropic materials. Most of these values re determined experimentally, elongations in arbitrary angles under the external load can produce more accurate results for design.

In the following section, the relationship between properties have been stated for a single-layer laminate in an arbitrary loading direction 1 which is making an angle (α) with the longitudinal fiber direction under no shear stress. If more than one load is applied on laminate, superposition methods can be employed to calculate the resulting stress which is making different angles with the longitudinal fiber direction (Ching Au).

I. Strain generated in the direction of applied stress

The applied stress (σ_1) causes a strain (ε_1) such that

$$\varepsilon_1 = \frac{\sigma_1}{E_1}$$

$$E_1 = \left[\frac{\cos^4 \alpha}{E_L} + \frac{\sin^4 \alpha}{E_T} + \frac{1}{4}\left(\frac{1}{G_{LT}} - \frac{2\nu_{LT}}{E_L}\right)\sin^2 2\alpha\right]^{-1}$$

II. Transverse strain generated by the applied stress

σ_2 causes a strain ε_2

$$\varepsilon_2 = -\nu_{12}\varepsilon_1$$

Where

$$\nu_{12} = \frac{E_1}{E_L}\{\nu_{LT} - \frac{1}{4}\left(1 + 2\nu_{LT} + \frac{E_L}{E_T} - \frac{E_L}{G_{LT}}\right)\sin^2 2\alpha\}$$

III. Shear Strain generated by the applied stress

When the external stress is applied in 1-direction acts at an angle other than 0 and 90 degrees with the fiber directions, shear distortion and hence shear strain γ_{12} will be induced. The following equation calculates the shear strain,

$$\gamma_{12} = -\frac{m_1 \sigma_1}{E_L}$$

In which m_1 can be found from

$$m_1 = \sin 2\alpha\{\nu_{LT} + \frac{E_L}{E_T} - \frac{1}{2}\frac{E_L}{G_{LT}} - \cos 2\alpha(1 + 2\nu_{LT} + \frac{E_L}{E_T} - \frac{E_L}{G_{LT}})\}$$

IV. Miscellaneous relationships of orthotropic Properties

The longitudinal and transverse Poisson's ratios are related as follows

$$\frac{\nu_{LT}}{\nu_{TL}} = \frac{E_L}{E_T}$$

And, G_{LT} can be theoretically calculated from experimentally determined data ν_{LT}, ν_{TL}, E_L, E_T from the following equation.

$$G_{LT} = \frac{E_L E_T}{E_L(1 + \nu_{TL}) + E_T(1 + \nu_{LT})}$$

It can be observed that this relation is in general form, isotropic relation can be deduced from this equation given the fact in isotropic, E_L equals E_T and ν_{LT} equals ν_{TL} (Ching Au).

2.2.2.4 Orientation Behavior

Arrangement of fibers and the interaction of the fiber reinforcement with adjacent matrix play a critical role in determining the mechanical properties of FRP composites such as if the fibers are chopped and embedded into the matrix randomly, then there will be isotropy and the laminate will be isotropic laminate. If continuous roving is present in orthogonal directions, there will be directional properties introduced in the laminate. In the primary fiber direction, there will be maximum strength. There will be inherent variation in the structural strength depending on the angle of loading, if the load and fiber orientation do not align with each then there will be significant reduction in structural efficiency. Fig shows a case of variation of strength with the angle of loading. This can be deduced by applying classical laminate theory on typical properties of E-glass unidirectional laminates (Ching Au).

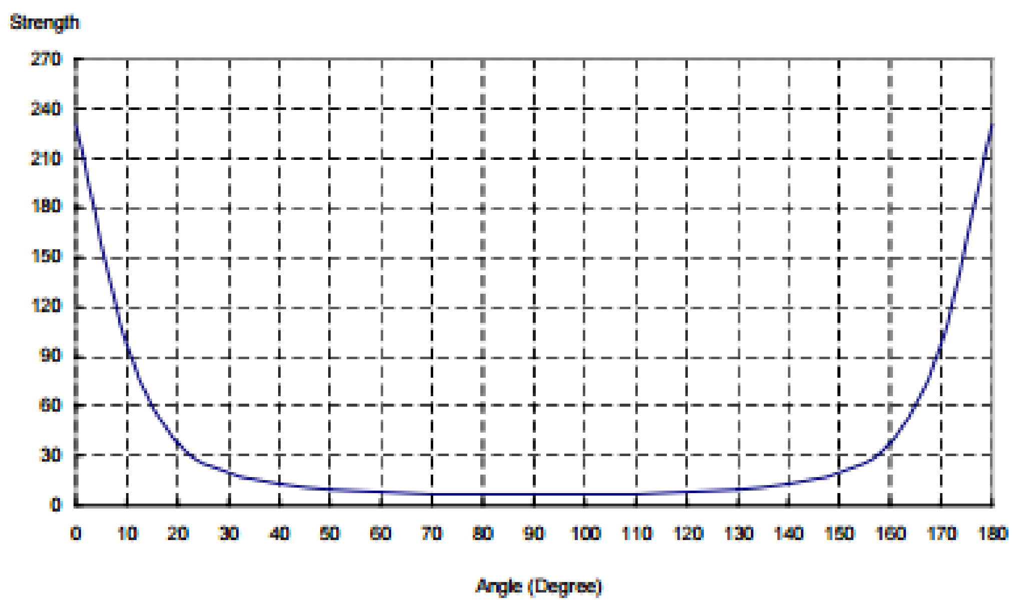

Figure 4 Typical strength variation with loading angle in a laminate with unidirectional fibers (Ching Au)

The orientation of fibers can also change the failure modes. In unidirectional fibers, there will be fracture in fiber direction if acted upon by tensile pull, the same laminated if loaded in the transverse direction, there will resin fracture since there are no fibers to resist load in that direction. Further, if the laminated makes an angle with the applied load, shear plane failure is predominant, in this, fiber may not fracture but the matrix experiences substantial shearing shear which is a force component decoupled from the tensile pull as demonstrated from the shearing strain equation.(Ching Au)

2.2.2.5 Creep Behavior

Creep is predominant in resin part of laminate and affects the molecular behavior of the material, so it is not of very much importance in the case thermosetting resin like epoxy because of the inherent interlocking of elements (molecules) during the curing process. Its intensity experienced depends on the temperature and magnitude of applied stress. The applied stress causes continuous strain on the molecular bonds in resin, the equilibrium is not attained for long periods of time so there will be deformations and upon removal of loads, there will irreversible deformations left on the matrix, hence creep is very critical in thermoplastic resins. On similar lines, temperature affects the molecular activity thus giving rise to more creep under higher temperature ranges. (Ching Au)

2.2.2.6 Fatigue Resistance

The stiffness of carbon fibers is very high which help them to bridge the cracks that occur across the matrix and hence reduce the stress intensity of the crack tip. Fatigue resistance Is relatively very low in less stiff glass fibers because of their stiffness and less effective stress transfer mechanisms from the matrix to the fibers, which results in matrix more prone to large stresses and promoting the crack development under a fewer load cycles compared to carbon fibers (Ching Au).

2.2.2.7 Impact Resistance

Impact load damage is dependent on the velocity and intensity of impact. This damage deteriorates the strength of composite laminates and this can be corroborated by test results (Ching Au) which state that delamination of the impacted re could be substantial, followed by peeling in the direction of the surface laminate fibers. In single layer laminate, impact resistance depends on fabric density, weave pattern and weave density. In addition of these, in multi-layer laminates the resistance also depends on interlaminate-shearing strength of the resin matrix.

2.2.3 Environmental Effects

2.2.3.1 Weathering

Degradation of matrix material is not critical and will not have direct effect on the strength and stiffness of the laminate because most of these mechanical properties are provided by the fibers only since they carry the external load. But the matrix should be able to evenly distribute the external applied stresses onto the fibers and it should be able to protect the fibers from micro-crack, moisture attack. So the protection of matrix is also important since degradation can be aggravated of upon excessive exposure to environment (Ching Au).

Weathering occurs in the form of UV radiation and thermal extremes. UV radiation causes change in molecular weights and also cross linking decomposition in the resin system. Whereas, thermal extremes mean there can be a season of high temperatures followed by a season of low temperatures thus they may occur in the form of freeze and thaw cycles such leading to cyclic thermal fatigue. Moisture in the next problem because of these cycles which attack the fibers directly and reduce the original strength through micro cracking. To prevent these three major issues protective coatings were developed and were found to be effective in preventing severe degradation of the FRP composite systems under service conditions (Ching Au)

2.2.3.2 Corrosion

If the moisture attacks in the presence of oxygen then it causes severe corrosion in steel. Rusting of steel and cracking of concrete covers are the noted problems which are difficult to tackle, corrosion in FRP composites is negligible even though the fibers are susceptible to the moisture attack and failure can be premature when load is applied in such conditions. But as discussed above, the resin matrix plays an important role in maintaining the integrity of the system by preventing fibers from moisture attack. The resin used in this study Sikadur Hex 300 exhibits excellent properties of moisture resistance before, during and after cure (manufacturer’s report).

2.2.3.3 Flammability

Temperature increase due to fire for long durations can have aggressive damage in the FRP properties. There will be matrix softening due to these elevated temperatures an this effect is based on matrix stacking and humidity. Quasi- isotropic stacking could effectively inhibit the strength reduction while unidirectional stacking experienced substantial strength reduction. This will also affect the fibers, notably PAN- based fibers. Oxidation was reported from experimental tests for such fibers (Ching Au).

2.3 Retrofit and Strengthening of Reinforced Concrete (RC) Structures.

2.3.1 Current Applications and Developments

Though FRP composite systems find their applications in reinforced concrete columns, beams, slabs, walls, chimneys, brick or block walls, structural wood systems, the substantial number of applications are found in RC structures. The forms in which FRP systems are available include FRP bar reinforcements, bonded plate systems, two-dimensional grid systems, confinement fabrics, and pre-stressing tendons which replace the traditional heavy steel reinforcements, jackets, or tendons.

Among the above mentioned techniques, FRP bar and bonded plate systems has gained success and improvement. The use of confinement fabrics has been souring during the past few years (20 year) cite here. But, analytical models that can predict the stress strain behavior accurately are still less. The designs which were previously used for steel confinements like steels jackets or spiral / circular reinforcements are successfully applied for confinement fabrics.

Furthermore, to rectify the issues of weathering and degradation of the composite systems, products like coatings which prevent them from fire, chemical attack, UV radiation and corrosion inhibitors have been developed to apply externally on these systems for their defense against such attacks.

2.3.2 Previous study on FRP strengthening of RC structural elements

2.3.2.1 Parretti and Nanni , University of Missouri –Rolla

Conducted tests to check the concrete confinement property of CFRP wraps with different fiber orientations including +_45- degree direction and different concrete cross section (circular and rectangular). The +-45 degree laminate's performance was compared with one whose fibers were in hoop direction. It was found out that the ultimate strength attained using +-45 degree laminate was less than that of unidirectional but the ductility was high in +-45 degree laminate because of enlargement of failure which ensured that higher amount of material participated in stress distribution, thus leading higher amount of energy dissipation. Previous numerical analysis support the experimental results. Suggestions were made in design guidelines for confinement of concrete with FRP laminates with different fiber orientations.

2.3.2.2 Esfahani, Kianoush, Ferdowski, University of Mashhad, Mashhad, Iran

This study included the experimental testing of six columns for axial compressive strength which confined by CFRP wraps. There were two series of specimens, each containing three. One series were circular in cross section, while other was square in shape with two specimens having sharp corners and one specimen rounded corners. Test setup included the displacement measurement, the results were compared with Canadian standard association code provisions, It was found out that CFRP increased the strength and ductility of circular columns notably. And there was increase in strength and ductility of square column with rounded corners compared to square columns with sharp corners, these results correlated well with the code provisions.

In addition of these works, there was also need for review of work done for material behavior which was very critical for modelling in ABAQUS CAE. Material behavior of concrete, steel, CFRP like mechanical properties were of predominant importance. Their interaction between each other was also included in the modelling. There are several constitutive material models for each of them (concrete, steel, CFRP).

2.3.2.3 Yasmeen Taleb Obaidat, Lund University, Lund, Sweden

In this study, a 3D nonlinear Finite element model framework was developed to simulate behavior of beams strengthened with CFRP. The program used was ABAQUS. Material models were taken from literature. Plastic damage was considered for concrete model. Steel was considered as a perfect elastic material. Bond between concrete and steel was considered as a perfect bond. The interface between concrete and CFRP modelled as a cohesive model, the input properties such as initial stiffness, fracture energy and shear strength were taken based on previous works, here fracture energy and shear strength were taken as functions of adhesive properties of tensile strength of concrete and of adhesive properties. Experimental values were compared with result from FEM. Different parameters were varied to check whether they affected the results like length, width of FRP. It was found that as the length of FRP increases the flexural and shear strength of beam increased. FRP to concrete ratio and the stiffness of FRP affect the failure mode of beams.

This study proposed to improve the calculation of interfacial shear stress at plate end in a design rule for simply supported beams bonded with FRP was proposed. Cite here

2.3.2.4 Adis Avdic, Ujjal Kumar Saha, University of Skovde

This work was focused on developing a numerical tool for simulation of tensile test on CFRP specimen and for efficient design of the multidirectional CFRP, this design was obtained through Finite element simulations. The program which was used for this purpose was ABAQUS/ CAE v 6.9-1, so that to generate 3D model of the tensile test on the composite specimen. The analysis of this multidirectional carbon fiber was done in order to predict the strain and stress distribution in various plies through thickness. In addition to this model, an experimental test was accomplished to co-relate the results from the model with this test. Tensile test experiment was carried out and the result was analyzed by

ARAMIS to find the stress, strain, loads and young's modulus of composite specimen. The comparison was done in order to investigate the strength and strain at failure of the composite material. In this study, there were types of CFRP composite specimens under investigation. Each of them had 15 number of plies oriented in different directions. It was found out that mechanical strength, failure load and strain differ slightly depending on this difference in ply orientation. For modeling also, different types of techniques were developed to see which one suited and verified as the best. Since micromechanics of composite material are complex and experimental investigations are time consuming, FEM can be used in these kind of study.

In addition to above works, ACI 440r design guide was used to predict the ultimate load and the failure mode of the specimens. These works were very important as they helped in carrying out experimental investigations, to predict the failure mode, ultimate strength, to develop a FEM framework to simulate the appropriate the material properties and to correlate the results from FEM and experiment.

Chapter 3

Experimental program

3.1 Specimen Preparation

When this study was started, specimen were already fabricated for testing. Four specimens were tested, one of them was control, two of them were wrapped with CFRP fabric with fibers along the hoop direction with one having single layer and other having double layer, one of them was wrapped with single layer CFRP fabric at +-45 degrees. Two strain gauges were installed at mid height of specimens which circumferentially opposite to each other. These gauges had 90 degree rosette so that longitudinal and hoop strain both can be measured at same time. The CFRP wrap was fabric cloth type, Sikawrap Hex 117C was the one used in this study and it was donated by the Sika USA.

3.2 Setup

The strain gauges installed were connected to strain box using cable extensions. The load cell was also connected to the strain box.

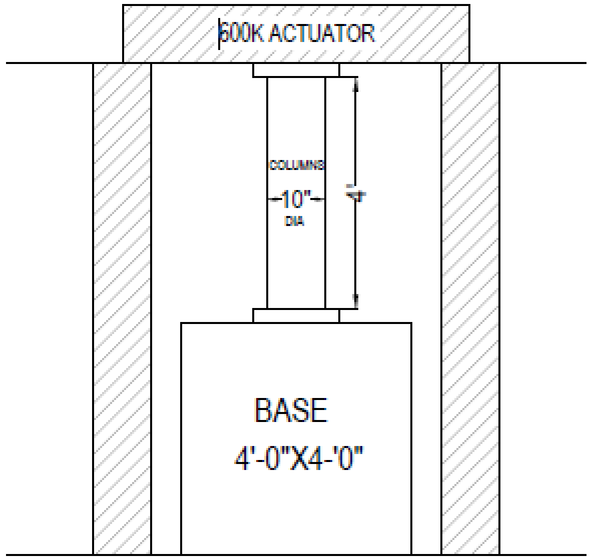

Figure 5 Schematic representation of the test setup which is employed in this experimental investigation

In the figure, the concrete block of 4’x4’ was grouted to strong floor of the lab. Upon that there was a steel plate 3” thick. This plate was grouted to the top surface of block. The column was then placed and it center was aligned along the center of the actuator. The bottom of column was grouted to the steel plate. The top of column was grouted another steel plate which was 2” thick so that the top face of column was flat and the load was distributed uniformly over the whole face and avoid the stress concentrations at any particular point. On the top of this plate there was there was load cell whose height was 7”. On this load cell there was actuator in place leaving a gap of 2”.

In the next section a picture is shown for the setup of testing. It does not have a laod cell on it but all other components are visible on it. The strain box was a good method of controlling the test. The laod was applied in steps to 44.48 KN (10 Kip). The laod cell readings were monitored with the help of the strain box. However, the laod capacity of the frame above the actuator was 2669 KN (600 Kip). This was recommended safe operating capacity of the setup.

Figure 6 Picture showing the test setup of the column at Civil Engineering Laboratory, University of Texas at Arlington

Chapter 4

Finite Element Model

4.1 Overview of software

ABAQUS Standard is an effective computer program which was used to model and simulate the material behavior of the specimen. The input for this program is typically the material properties. The materials in this study like concrete, steel and CFRP are modelled based on the models present in the literature. Then the interaction between these materials was also studied carefully and then they were modelled in a proper way such that it represent the real interaction. After modeling, this software allows to perform analysis of the job which include but mot limited to stress vs strain curves at various points, load vs strain, load vs displacement. Displacement controlled analysis was used here to find the peak load and behavior after the peak load. In this kind of analysis, an initial displacement is assigned on top face of the column and if the peak load is reached the analysis stops displaying error and if the peak load is not reached then analysis is completed and initial displacement value can be increased until there is error in the analysis. So, it is easy to find peak load in this kind of analysis because if it is force controlled then, initial load has to be defined in increasing steps making the process cumbersome as the peak load value is not known.

4.2 Material Models

4.2.1 Concrete

Concrete was defined as a plastic damage model since this program has the capability to model concrete damage plasticity, the parameters were defined as in the work of Obaidat. Concrete is modelled for compression damage and tension damage. This model assume that two basic mechanisms were compressive cracking and tensile softening.

To start with the stress strain model, compressive strength is given as an input. Cylindrical specimens were casted using ACI mix design and tested for their compressive strengths at the age of 7 days. According to ACI provisions, the minimum compressive strength for 7 days is 24.131 MPa (3500 Psi). Table below gives the detailed strengths of each sample.

Table 4-1 Values for compressive strength obtained from testing of specimen (Vinod)

Sample	**Age**	**Typical Values**
Sample 1	7 days	27.468 MPa (3984 Psi)
Sample 2	7 days	30.536 MPa (4429 Psi)
Sample 3	7 days	32.267 MPa (4680 Psi)

The average compressive strength at the age of 7 days is 30.09 MPa (4365 Psi). To calculate the 28 da compressive strength, it should be noted that 28 day strength can be taken between 1.4 and 1.7 times the 7 day compressive strength (Concrete Microstructure, properties and materials, Mehta, Monteiro). In this study 1.4 was taken as the optimum coefficient, thus 28 day average compressive strength is 43 MPa (6236 Psi). This value was carried forward for further calculations in developing the stress strain response of concrete under uniaxial compression.

4.2.1.1 Concrete behavior under uniaxial compression

Concrete behavior under compression is given in vast number of works. However, some of the most popular are used for modelling in ABAQUS. The initial known value of compressive strength is useful here. It helped in developing the stress-strain response.

Firstly, Modulus of elasticity was obtained from equation (Obaidat)

$$Ec = 4700\sqrt{f'c}$$

The stress-strain response can be generated using the relation (Obaidat)

$$\sigma_c = \frac{E_c \varepsilon_c}{1 + (R + R_E - 2)\left(\frac{\varepsilon_c}{\varepsilon_o}\right) - (2R - 1)\left(\frac{\varepsilon_c}{\varepsilon_o}\right)^2 + R\left(\frac{\varepsilon_c}{\varepsilon_o}\right)^3}$$

Where,

$$R = \frac{R_E(R_\sigma - 1)}{(R_E - 1)^2} - \frac{1}{R_E},\ R_E = \frac{E_c}{E_O},\ E_o = \frac{f_c'}{\varepsilon_o}$$

And, ε_c = 0.003, R_σ = 4, Poisson's ratio was taken as 0.2 (Obaidat). The stress strain behavior of concrete is represented in the figure below. The above relations give the following values

Table 4-2 Values obtained from the constitutive relations used in the model

Strain	Stress in MPa	Stress in Psi
0	0	0
0.0005	9.85654628	1430.0173
0.0008	14.1390184	2051.33121
0.0011	18.4416612	2675.57153
0.0014	23.0315228	3341.48242
0.0017	27.9347804	4052.86175
0.002	32.940342	4779.08364
0.0023	37.5666348	5450.28008
0.0026	41.1124955	5964.72419
0.0029	42.8838892	6221.7233
0.003	43.0045953	6239.23571
0.0035	40.2635804	5841.56104
0.0036	39.1810143	5684.4991
0.0039	35.3397926	5127.20313
0.0042	31.1291166	4516.30562
0.0045	27.0376879	3922.70887
0.0048	23.328896	3384.62621
0.0051	20.0994701	2916.09143
0.0056	15.7612371	2286.68756
0.006	13.0925913	1899.51243
0.0064	10.9822196	1593.33336
0.0068	9.30493286	1349.98757
0.007	8.59655257	1247.21364
0.0076	6.87374136	997.263017
0.008	5.9855344	868.399287
0.0085	5.08986247	738.452516
0.009	4.37548727	634.80882
0.01	3.32538991	482.457544
0.015	1.21750652	176.639498
0.02	0.6220353	90.2467475
0.025	0.37605054	54.5585402
0.03	0.25150802	36.4895375

The above obtained values will result in the stress-strain curve as given below

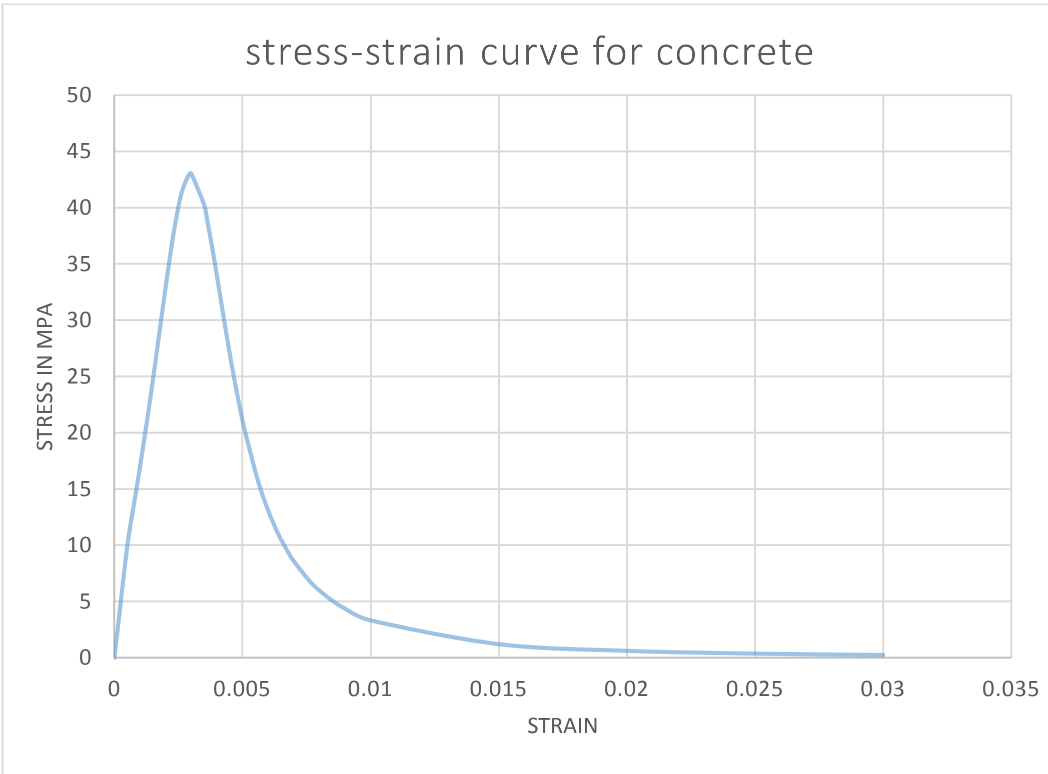

Figure 7 Stress strain model of concrete used in this study

By using the above response curve, the values of yield stress and their corresponding inelastic strain can be found out. These values were given as an input to the program. Inelastic strain can be calculated from total strain by the equation

$$\varepsilon_{in} = \varepsilon_c - \varepsilon_o$$

4.2.1.2 Concrete behavior under uniaxial tension

Under uniaxial tension, the response of concrete is linear elastic until the failure stress is reached, at the failure stress, there will be onset of micro cracking in concrete material, thus softening stress-strain response represent the response beyond failure stress. To develop the first part of the response, elastic parameters like elastic modulus E_c and tensile strength f_{ct} have to be calculated using the following relations (Obaidat)

$$\mathrm{E_c} = 4700\sqrt{\mathrm{f'_c}} = 30820 \text{ MPa}$$

$$\mathrm{f_{ct}} = 0.33\sqrt{f'_c} = 2.16 \text{ Mpa}$$

Where f'_c is given in Mpa, 43 Mpa.

To define the post peak tensile failure behavior of concrete, fracture energy method is used. The fracture energy for model, G_f is the area under softening curve and ws assumed equal to 90 J/m^2

4.2.2 Steel Reinforcement

The steel was considered as an elastic- perfectly plastic material and its behavior to be identical in tension and compression (Obaidat) as shown in fig. Poisson's ratio was assumed to be 0.3 and Elastic Modulus was taken as $\mathrm{E_s} = 200 \text{ Gpa } (29000 \text{ Ksi})$ and $f_y =$

507 Mpa (75 Ksi) and these values were taken FEM study (Obaidat). The perfect between steel and concrete was considered.

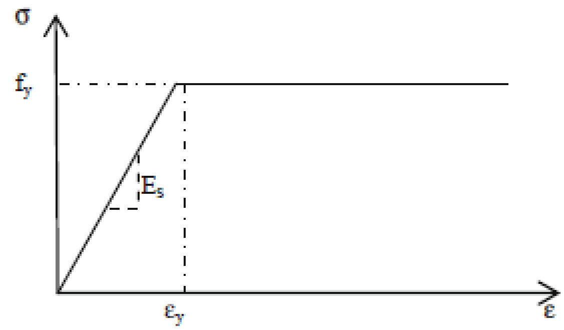

Figure 8 Stress strain model of steel used in this study (Obaidat)

4.3.3 CFRP

The CFRP material used here was Sikawrap® Hex 117 C, which is a unidirectional carbon fiber fabric. Material is field laminated using either Sikadur 300, Sikadur Hex 300/306 or Sikadur 330 epoxy to form a carbon fiber reinforced polymer (CFRP) used to strengthen structural elements. (Product data sheet Sikawrap Hex 117C). More detailed version of the properties of the laminate used in the study can be seen below.

Table 4-3 Typical data of Sikawrap® Hex 117C (Product data sheet, edition 5.5.2011, Sikawrap Hex 117C)

Storage conditions	Store dry at $4^0 – 35^0$ C ($40^0 – 95^0$ F)
Color	Black
Primary Fiber Direction	0^0 (unidirectional)
Weight per Square Yard	300 g/m^2 (9.0 oz.)
Cured Laminate Properties	Design Values

Tensile Strength	724 Mpa (1.05 x 10^5 Psi)
Modulus of Elasticity	56,500 Mpa (8.2 x 10^6 Psi)
Elongation at Break	1.0 %
Thickness	0.51 mm (0.02 in.)
Strength per Inch Width	9.3 KN (2100 lb/layer)
Fiber Properties	Design Values
Tensile Strength	3,793 Mpa (550000 Psi)
Tensile Modulus	234,000 Mpa (34 x 10^6 Psi)
Elongation	1.5 %
Density	1.8 gm/cc (0.065 lb/in^3)

Majority of the composite materials are made by stacking several distinct layers of unidirectional lamina or ply. The composite material here is a laminate which is formed by single lamina with primary orientation of fibers in one direction along longitudinal axis (0^0) to achieve the desired mechanical properties. Fig shows a unidirectional lamina with respective longitudinal and transverse directions (Avdic and Saha). To model it in ABAQUS, it is important to know the stiffness of individual lamina. The stiffness of lamina and laminate depends on three factors (Avdic and Saha):

1. Volume fraction of the matrix and fiber
2. Type of reinforcement used, continuous or discontinuous fiber used.
3. Orientation of fibers with respect to a common reference axis.

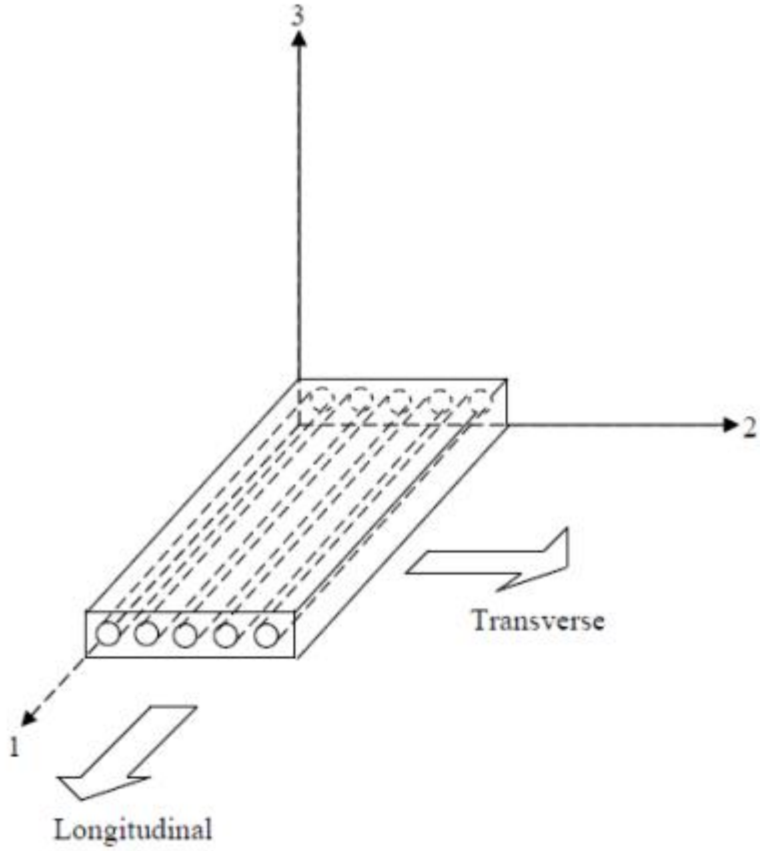

Figure 9 Schematic representation of a typical unidirectional lamina with fibers in one direction only (Avdic, Saha)

4.2.4 Stiffness of composite lamina according to rule of mixture (Avdic, Saha)

Some assumptions are made for unidirectional lamina like, it is assumed that the fibers are bonded perfectly to the matrix without any slippage which enables them to experience the same strain and the fibers are parallel throughout the whole composite. This iso-strain condition discussed before can be represented as,

$$\varepsilon_c = \varepsilon_f = \varepsilon_m$$

Rule of mixture notes that if an axial load is applied in the longitudinal direction it will be shared by the fiber and the matrix, and which is given by;

$$P_c = P_f = P_m$$

Or, $$\sigma_c A_c = \sigma_f A_f + \sigma_m A_m$$

These expressions can be simplified to

$$E_c = E_f V_f + E_m(1 - V_f) = E_{11}$$

Where, E_{11} is the longitudinal elastic modulus of the composite lamina.

To calculate the transverse stiffness, load is assumed to be applied at right angles to the fiber direction or transverse direction, as shown in fig and it produces equal stresses in fiber and matrix, which is called iso-stress situation. This results;

$$\sigma_c = \sigma_f = \sigma_m$$

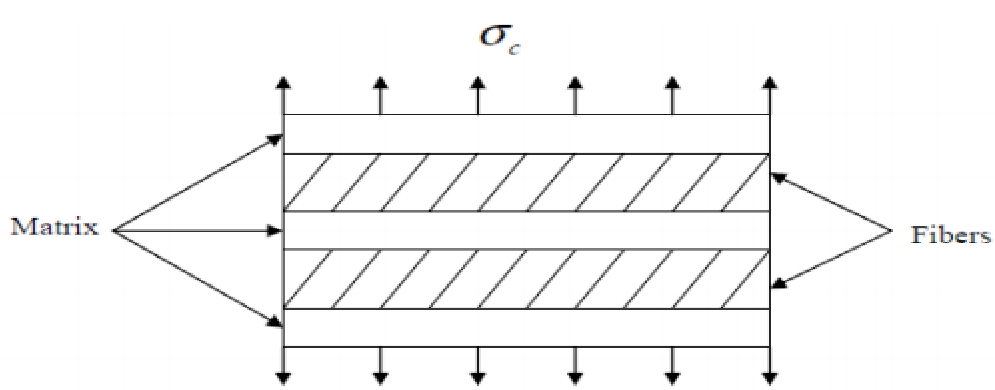

Figure 10 Arrangement of matrix and fibers in a laminate (Avdic, Saha)

The composite elongation (δ_c) in the direction of the load is equal to sum of elongation of fiber (δ_f) and elongation of matrix (δ_m),

$$\delta_c = \delta_m + \delta_f$$

The transverse stiffness can be calculated using the rule of mixture and above two equations,

$$E_{22} = \frac{E_f E_m}{(E_f V_m + E_m V_f)}$$

To calculate the shear modulus, the equal stress distribution which was used for transverse modulus can be used here, i.e,

$$\tau_C = \tau_f = \tau_m$$

From fig below, the deformation can be written as,

$$\Delta_c = \Delta_f + \Delta_m$$

From the above two relation, the equation for shear modulus can be derived as;

$$G_{12} = \frac{G_f G_m}{G_f V_m + G_m V_f}$$

Unidirectional composites are orthotropic in nature and have same stiffness properties in the transverse directions, so

$$E_{22} = E_{33}$$

$$G_{13} = G_{12}$$

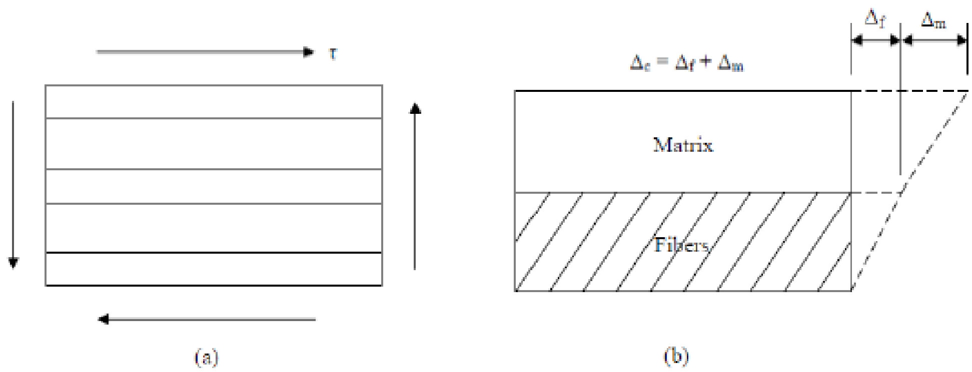

Figure 11(a) Unidirectional composite under in plane shear loading, 11(b) deformation of the unidirectional composite under shear loading.

4.3 Part and Geometry

There should different parts created in ABAQUS for different constituents of the specimen like concrete, steel, CFRP. For steel reinforcement, there are two parts to define, one for the longitudinal reinforcement and other for transverse reinforcement (ties).

4.3.1 Concrete

Since it is a circular column, the circular cross section can be defined by drawing a circle of 25.4 cm diameter and extruding it for a length of 121.92 cm. This part is defined as a solid in ABAQUS.

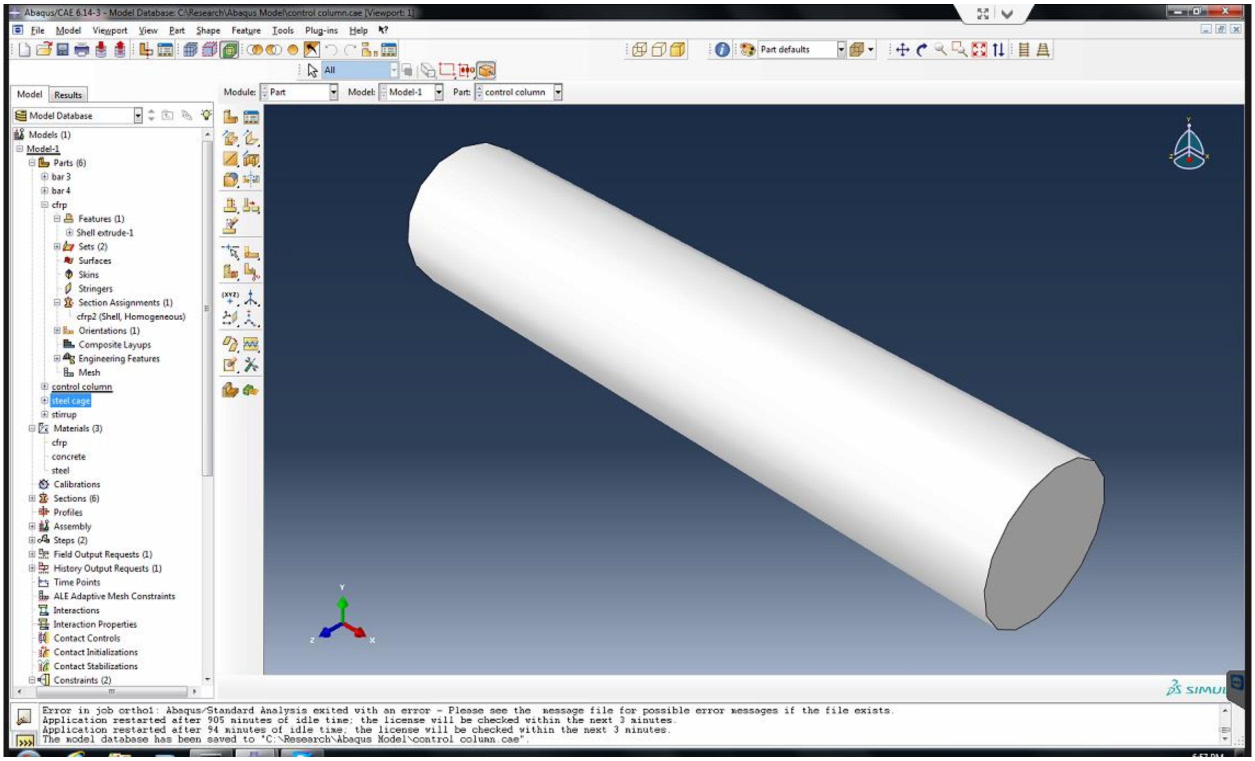

Figure 12 Snapshot from ABAQUS program showing the concrete part in the model

4.3.2 Steel

For this part, longitudinal bars and ties have to be created and assembled. For this, a sketch of two longitudinal bars of length 114.3 cm are drawn with a distance between them 7.14 cm, this distance is calculated considering a clear cover of 5.08 cm and two times diameter of ties 1.905 cm. In assembly module, this part is added as an instance and using the radial pattern tool, all the bars are arranged in radial pattern. The bottom bar is taken as the axis of rotation for the pattern and the above bar is selected as the entity to be patterned. The required number of entities in the pattern is selected as six and then the middle bar is suppressed in the assembly.

Similarly, for ties, one tie is created in part module, as wire element with thickness equal to diameter of tie, i.e., 0.9525 cm and diameter of this element equal to the diameter of radial pattern. This tie is added as an instance in the assembly module, and this instance can be copied at the spacing of 12.7 cm along the length of the longitudinal bar, thus producing 9 ties. This results in steel cage as shown in fig below.

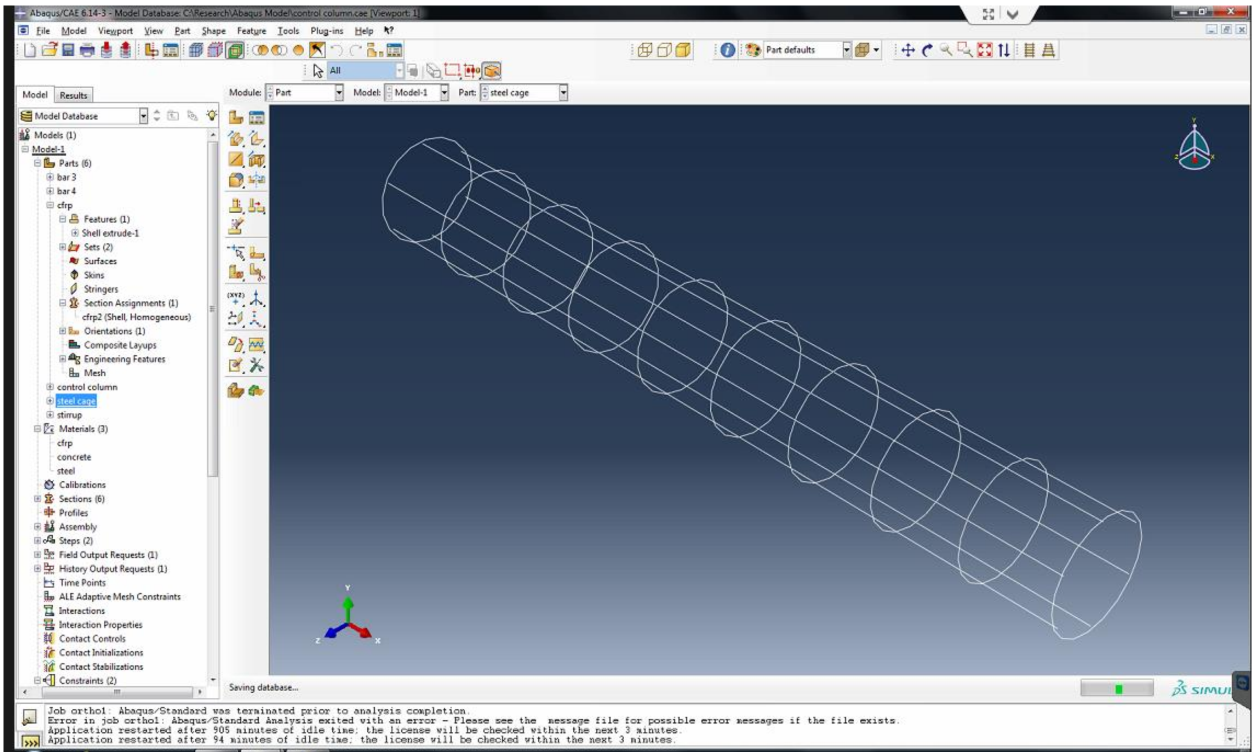

Figure 13 snapshot from the model showing the reinforcement for the model

4.3.3 CFRP

This part is defined as shell element with extrusion equaling to column length, and added to the assembly as an instance and overlapped over the concrete column. This is modelled as an elastic material with selecting Engineering constants as one of the types in the dialog box. In property module, composite layups are defined as given by the manufacturer.

Thickness, material type, orientation are given as input in this dialog box. Insert the table here

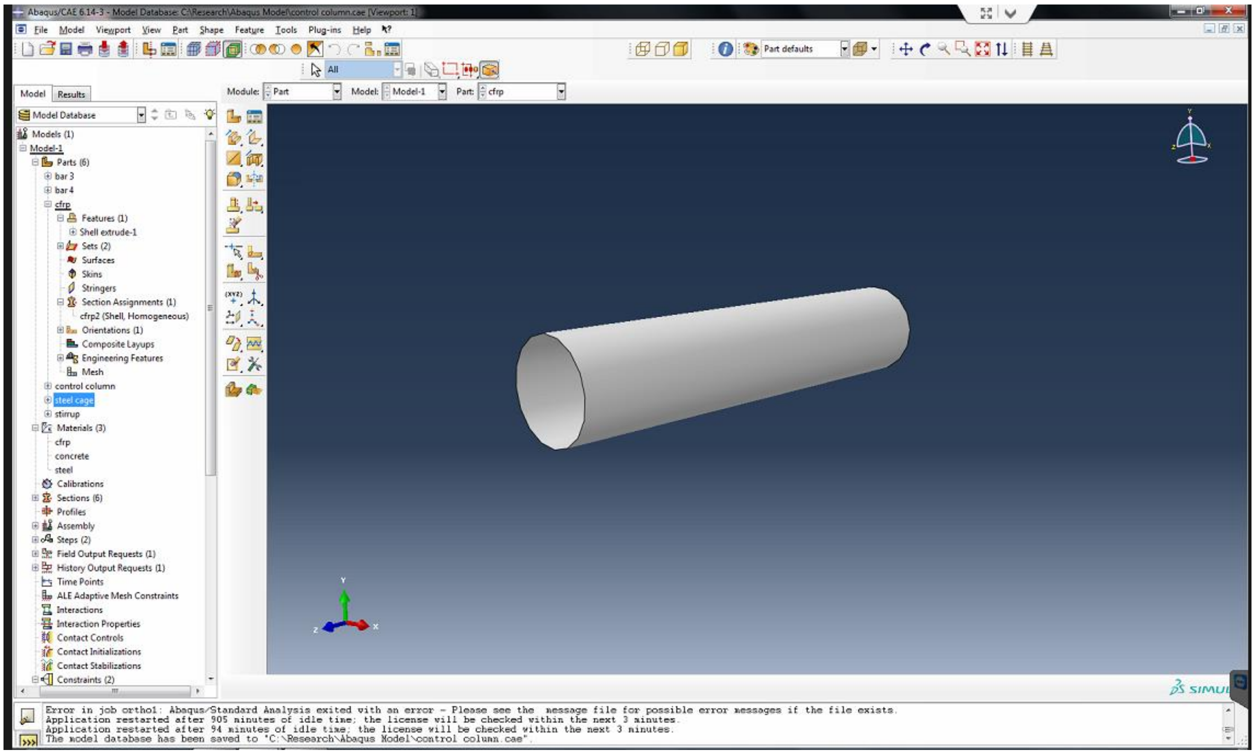

Figure 14 CFRP laminate being modeled as a shell element in ABAQUS

4.4 Section Assignments

Sections are assigned for the parts above as solid, homogenous for concrete part, truss for steel part and shell, composite for CFRP.

4.5 Interactions

In ABAQUS, user has to define the interaction between different instances present in assembly module. For this, in interaction module, constraints has to be created. For steel and concrete a constraint of type “embedment” has to be created. In this type host region has to be concrete part and embedment has to be steel cage. Other constraint used was interaction between concrete and CFRP laminate. A tie constraint was defined with master nodes being concrete and slave nodes being CFRP and coarser mesh being the master surface and finer mesh being slave surface.

4.6 Boundary conditions

The bottom surface of the column was fixed (Encastre), to attain this bottom most elements of the column were fixed. Those elements can be seen in the fig below as colored ones.

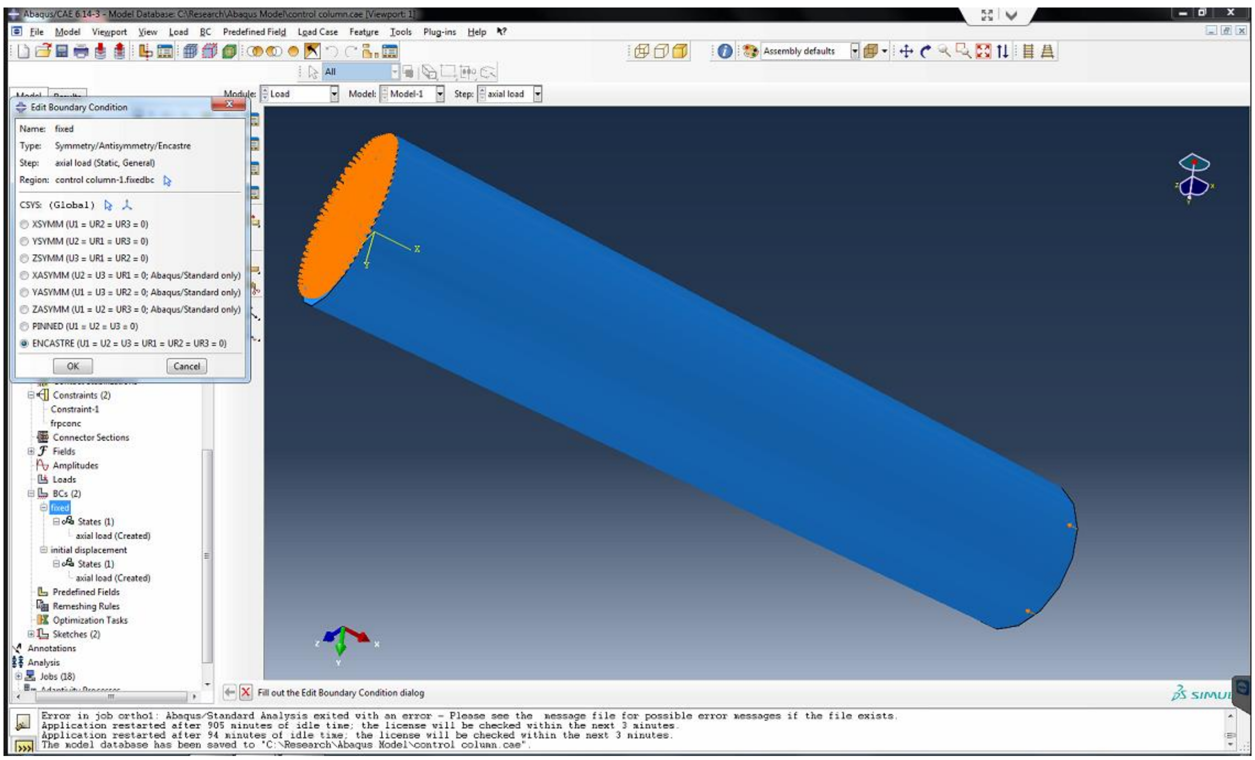

Figure 15 Fixed boundary condition being applied on the bottom face of assembly in the model

4.7 Assigning Mesh

Mesh creation is very important for any Finite element analysis. It is very critical for engineering simulation. This procedure divides the model into various small elements which is very important to generate accurate results. Smaller mesh size will give higher number of elements, thus higher accuracy. This will result in longer time for completing the analysis. So an optimum mesh size has to be chosen to attain the appropriate results.

To create a mesh, each part has to be meshed differently, to make them independent from each other, for this, meshing is done in part module instead of assembly module. Firstly, seeding is done on the part, then mesh elements are assigned and then region is selected for which meshing has to be done.

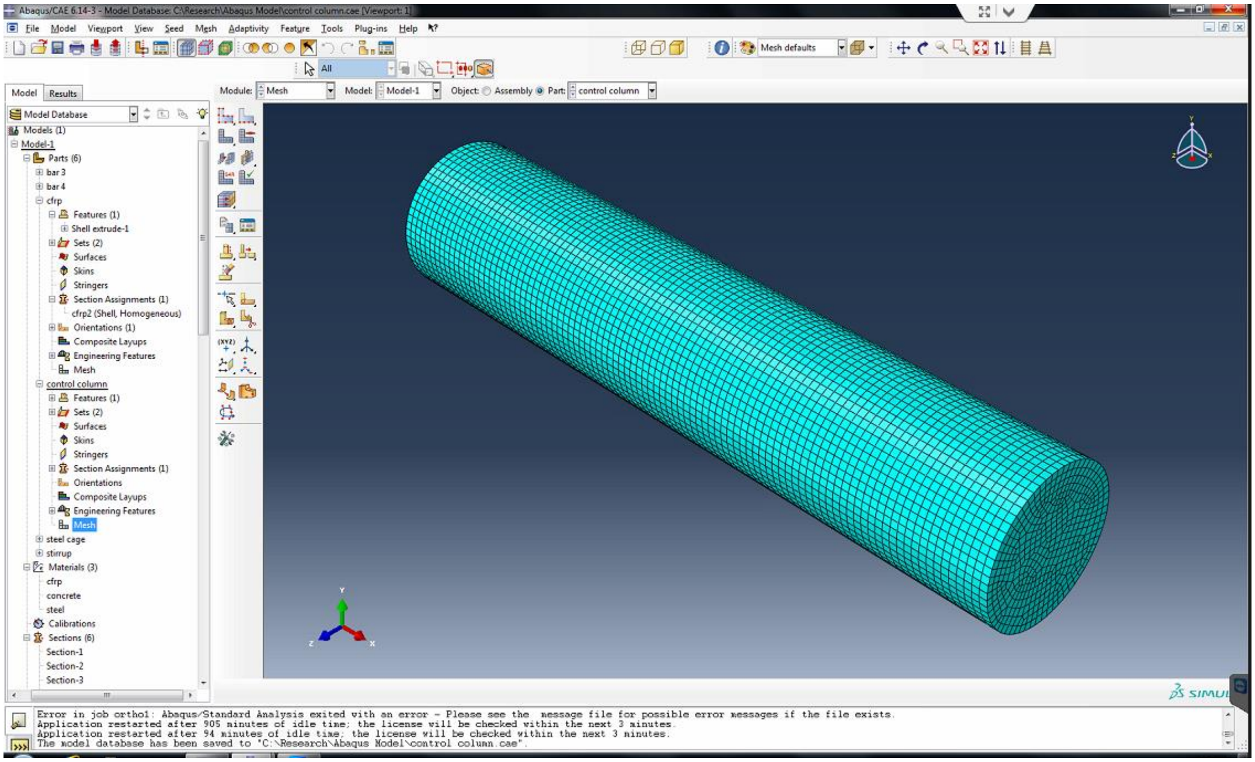

Figure 16 Mesh created on the assembly of the model

4.8 Defining Step

In this, external load/initial displacement had to be assigned on the column. Since study was dealing with only uniaxial compression, only axial load along the longitudinal axis was defined. For this, initial displacement was defined on the top surface of the column along the longitudinal direction which allowed to find the peak load for the specimen. The progress of the job (analysis) can be monitored on job monitor. If the job is fully completed then there might be possibility of increasing the initial displacement. So, the displacement has to be increased in steps and at some displacement value, the full analysis is not completed. At this stage, it is understood that the load (reaction force) obtained is the ultimate load. The results can be obtained in visualization module of the program.

Chapter 5

Results

The objective of this section is to present the results from Finite Element Analysis and Design Equations primarily since the experimental program was not equipped to test the specimen with such high peak loads. The setup was able to fully test only one specimen which was control specimen (without any wraps).

ACI.2R -08 and NCHRP are two standard guidelines with which the results from FEA are being tested in this section. Four specimens in this study include control, 1 layer horizontal wrapped column (denoted by C1), 2 layer horizontal wrapped column (denoted by C2), 1 layer inclined (45 degree) wrapped column (denoted by O1). For this purpose, the guidelines from ACI and NHCRP are used to calculate the axial confined concrete compressive strength (f'_{cc}) and ultimate axial compressive strain in concrete (ε_{ccu}). Table shows the characterstic of specimen which are considered in this study. The first column represents the number of layers of CFRP wraps and their orientation : H= horizontal (perpendicular to longitudinal axis), O= inclined/ oblique, the number succeeding the letter represents the number of layers. The shape of ll the specimens is circular, so there is no specific notation for the shape. D is the diameter of the cross section, H is the total column height, A_g is the gross sectional area of column section, ρ_f is the fiber reinforcement ratio, ρ_l is the ratio of longitudinal steel reinforcement, f'_c is the concrete compressive strength based on standard cylinders, f_y is the yield stress of the steel.

Table 5-1 Specimen characteristics

Specimen	D (mm)	H (m)	A_g (cm^2)	ρ_f (%)	ρ_l (%)	f_y (MPa)	f'_c (MPa)	$\frac{f'_{cc}}{f'_{co}}$	$\frac{\varepsilon_{ccu}}{\varepsilon_{cu}}$
C1	254	1.22	506.8	0.8	2.36	414	43	2.194	6.26
C2	254	1.22	506.8	1.6	2.36	414	43	3.55	14.56

Here f'_{co} is the compressive strength of the unconfined concrete obtained from the peak load value of the control column minus the contribution of steel divided by the cross section concrete area. ε_{cu} is the ultimate strain in the unconfined concrete to be taken as 0.003 (ACI). ε_{ccu} is the ultimate strain in confined concrete to be taken from FEA. The parameters in the last two columns of this table are taken from the FEA.

In the next table, the theoretical values of the parameters like confined concrete compressive strength, confined concrete ultimate axial strain are shown. These values are calculated from the equations stated in ACI 440.2R- 08 and NCHRP Report 655 which has the design recommendations of externally bonded FRP systems for repair and strengthening of concrete bridge elements for AASHTO.

Table 5-2 Values obtained from the design guidelines

Guideline	Specimen	f'_{cc} (MPa)	$\frac{f'_{cc}}{f'_{co}}$	ε_{ccu} (mm/mm)	$\frac{\varepsilon_{ccu}}{\varepsilon_{cu}}$
ACI	C1	56.9	1.42	0.0062	2.06
	C2	68.2	1.70	0.0092	3.07
	O1	NA	NA	NA	NA
NCHRP	C1	51.3	1.28	NA	NA
	C2	54.6	1.36		
	O1	NA	NA		

In the table , the comparison of the values from the guidelines and from thee FEA is done. Primarily the comparison is done for the confined concrete compressive strength and for the ultimate axial strain.

Table 5-3 Comparison of design guidelines equations with FEA in terms of confined compressive strength and ultimate strain

Guideline	Specimen	$\frac{\left(f'_{cc}/f'_{co}\right)_{Theo}}{\left(f'_{cc}/f'_{co}\right)_{FEA}}$	$\frac{\left(\varepsilon_{ccu}/\varepsilon_{cu}\right)_{Theo}}{\left(\varepsilon_{ccu}/\varepsilon_{cu}\right)_{FEA}}$
ACI	C1	0.64	0.33
	C2	0.47	0.21
	O1	NA	NA
NCHRP	C1	0.58	NA
	C2	0.38	

	O1	NA	

It can be observed here that none of the design guidelines have any provisions for the inclined wrapping and in the case of regular wrapping, there is no provision for strain in NCHRP.

In the table, there is a comparison of the values of peak loads from equations and the FEA. Notably, here also there is no provision in the guidelines for inclined wrapping.

Table 5-4 Comparison between design guidelines and the FEA in terms of peak load values

Guidelines	Specimen	P_{theo}/P_{FEA}
ACI	H1	0.57
	H2	0.43
	O1	NA
NCHRP	H1	0.52
	H2	0.36
	O1	NA

The FEA model developed in this study can be further verified with the results obtained from similar study. The study of Silvia Rocca, Nestore Galati and Antonio Nanni has the experimental verification of the design guidelines for these type of specimen. The results of their study along with FEA results of this study are presented in the table below.

Table 5-5 Results from the study of Silvia Rocca et al. in first two columns, ratio of peak load from experiment to peak load from FEA of this study are in the last column

Design Gudieline	P_{theo}/P_{exp}	P_{theo}/P_{FEA}
ACI	0.61	0.57
CSA	0.52	NA
Concrete Society	0.87	NA
Fib "Exact"	0.86	NA
Fib "Practical"	0.70	NA

From the above comparison, it can be noted that FEA model was able to simulate appropriate response of the specimen under consideration. The slight variation in the ratio is due to the fact that fiber reinforcement ratio of the other study is 0.26 % compared to 0.8 % of this study (Table 5-1). If the fiber reinforcement ratio is higher, then it will have higher confinement effect thus resulting in the increase in the peak load.

For all analytical calculations, all the safety and material factors were set equal to 1 to develop similar situation as in the model of FE. The FRP systems provide the confining pressure against the radial expansion of the concrete core so that the dilation of core can be prevented if the fibers are aligned transverse to the loading. There are no provisions and experimental data to develop equations if the fibers are inclined at an angle other than 90 degrees to the loading (ACI 440.2R-08).

According to NCHRP, the column under study can be classified as short column if L_u/D ratio is at least 8, in our study, this ratio is 4.80, where L_u is unsupported length of the column and D is the diameter.

In the figure 17, the load deflection curve for 1 layer horizontal wrap can be seen. The ductility increase of the specimen can be witnessed in the curve.

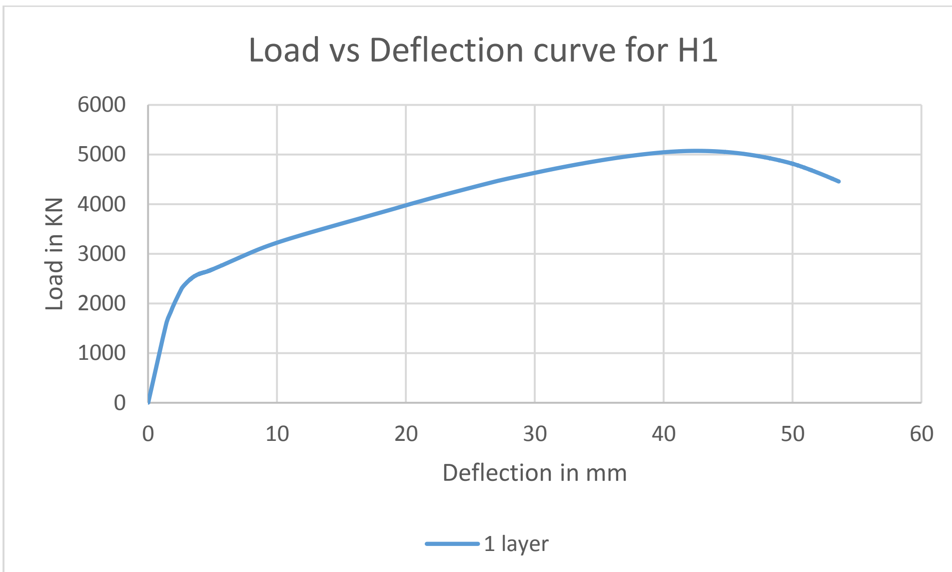

Figure 17 Load vs deflection curve for H1 specimen

In the figure 18, the load vs deflection curve for the specimen H2 with two horizontal wraps can be seen.

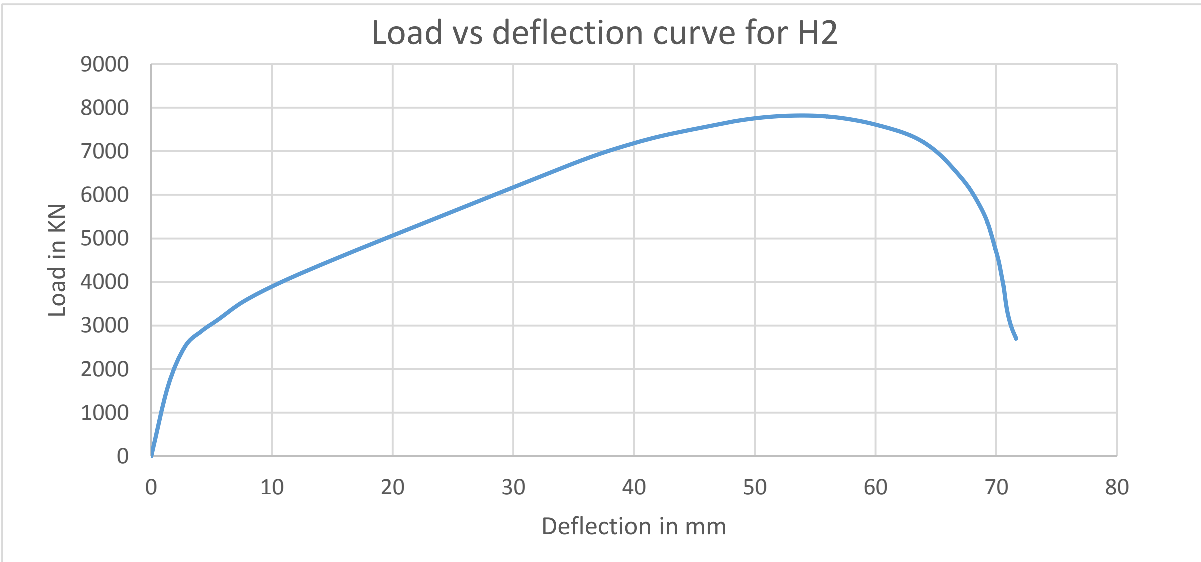

Figure 18 Load vs Deflection curve for H1

In the figure 19, the load vs deflection curve for the specimen O1 with inclined wraps can be seen.

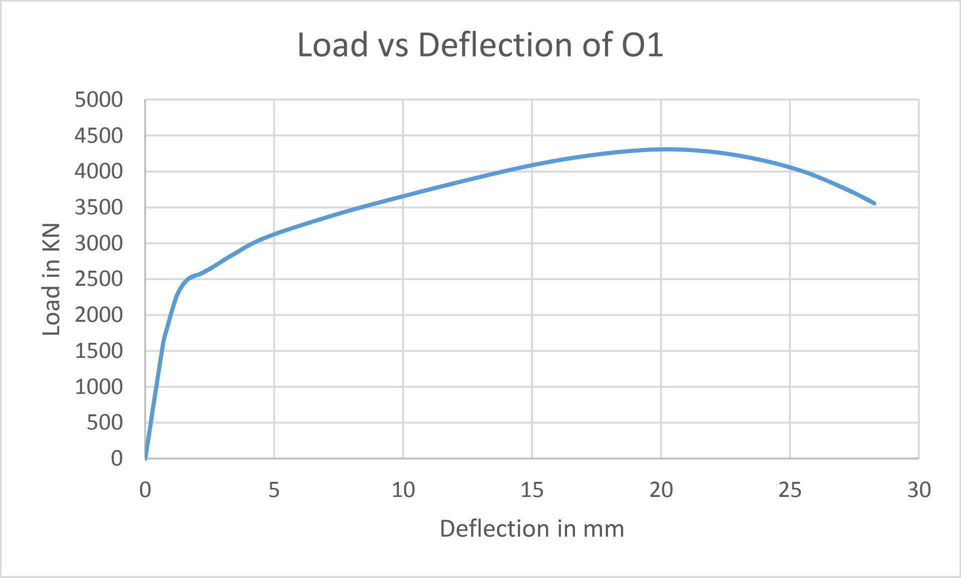

Figure 19 Load vs Deflection Curve of O1

These curves can be compared to the control column which has no CFRP confinement by looking at the curve of control column in figure 20.

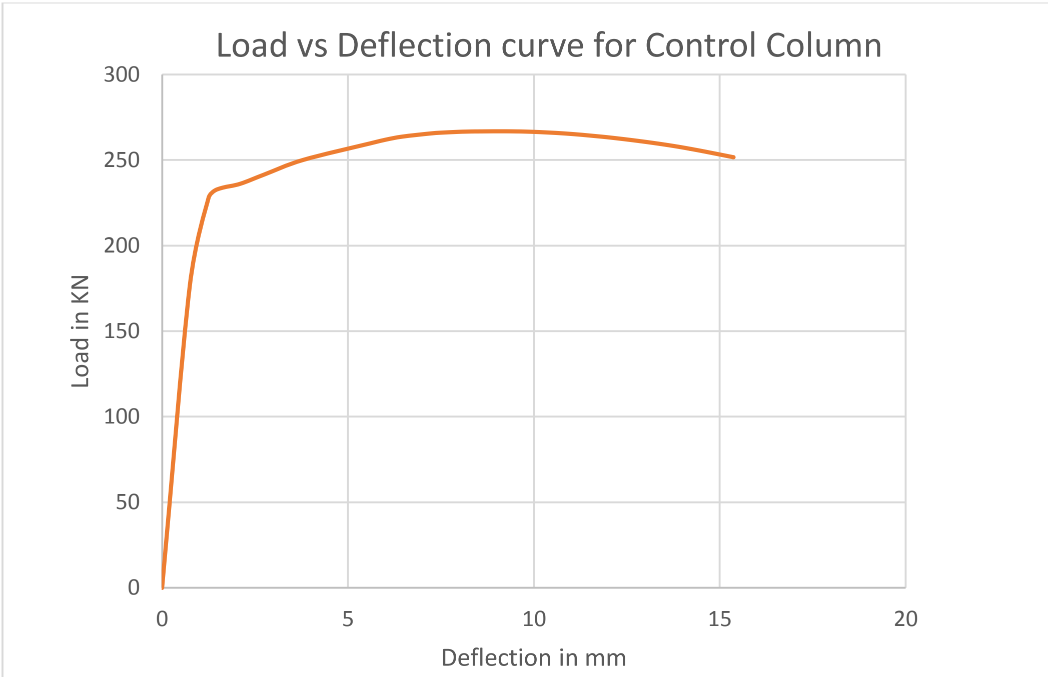

Figure 20 Load vs deflection curve for Control

The stress vs strain curve for H1 (1 layer horizontal wrapped specimen) can be seen below. This curve is mentioned to explain about the typical failure mode of all specimen. In this study, the tensile rupture of CFRP is considered to be main failure mode of the specimen. The de- bonding failure can also one of the failure modes but in the model, the tie pair assembly between concrete surface nodes and the CFRP sheet nullifies the de- bonding of CFRP. Hence, the tensile rupture is considered main mode of failure of specimen. To examine whether specimen had failed, the ultimate strain obtained from stress strain curves is noted in all cases. Curve for 1 layer horizontal is shown in Figure 21 and it can be seen that ultimate strain is 0.018. From Table 5-2, it can be observed that the expected ultimate compressive strain in confined concrete from design equations was 0.0062 in H1 and 0.0092 in H2 and it was restricted to 0.01 by ACI 440.2R and the ultimate tensile strain in CFRP from manufacturer was also 0.01. But, the FEA results suggest higher strain values given the fact that the model from code does not have decreasing branch in stress strain curve to control the excessive cracking in concrete and loss of concrete integrity. So there can be more study oriented towards this part of stress strain curve of confined concrete which may give higher strains for code equation. Hence, it can be concluded that the values through this analysis were ultimate in terms of peak load, axial stress, axial strain, deformation.

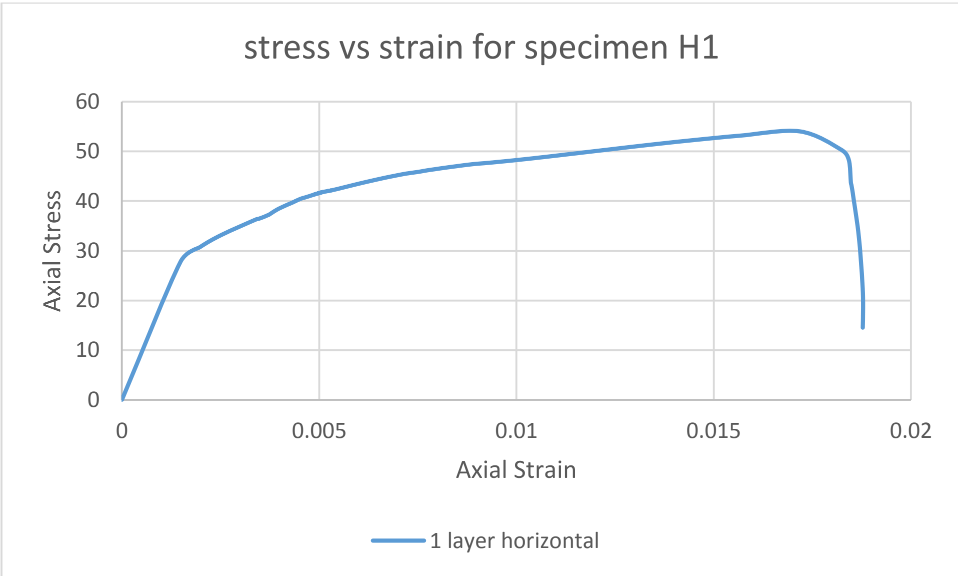

Figure 21 Stress strain curve for H1

It can be seen that the CFRP wraps have high efficiency in improving the strength and ductility of the specimen. The failure of the CFRP was due to tensile rupture, however there are some difficulties in the installation of CFRP in square and rectangular specimen.

Chapter 6

Discussions

6.1 Discussion

In this study, the experimental investigations were not really helpful in finding out the peak load values of the wrapped specimen as it can be witnessed from the prediction of the design guidelines. The prediction is not accurate and hence the setup was not equipped to carry out the full scale test of the specimen. However, the FEA on ABAQUS program carried out in this study was helpful to compare the results from it with the design guidelines. The accuracy in the predicting the peak values of load, compressive strength and axial strain can be improved if the f_l value is increased in both the equations of ACI and NCHRP. Equations of f'_{cc} of both the guidelines can be observed as below,

ACI: $f'_{cc} = f'_c\left[2.25\sqrt{1 + 7.9\frac{f'_l}{f'_c}} - 2\frac{f_l}{f'_c} - 1.25\right]$, $f_l = \frac{2E_f n t_f \varepsilon_{fe}}{D}$

NCHRP: $f'_{cc} = f'_c\left(1 + \frac{2f_l}{f'_c}\right)$, $f_l = \varphi_{frp}\frac{2N_{frp}}{D} \leq \frac{f'_c}{2}\left(\frac{1}{k_e\varphi} - 1\right)$

It can be observed from these equations, Compressive strength of confined concrete is highly dependent on the confining strength f'_l, which is lesser from ACI equation than from NCHRP equation. This value can be increased to increase f'_{cc} value but it will in return lead to increase in allowable transverse strain thus there will be loss in concrete integrity and excessive cracking. Thus an optimum value of f'_l should be recommended to improve the accuracy of the equations. The equation of ACI is directly deputed from Mander formula (Rocca).

Further, according to NCHRP minimum value of f'_l should be taken as 600 psi even this value seems to have not improve the accuracy. Hence, either the f'_l should be optimized or the equation defining f'_{cc} should be given any recommendations.

The strain efficiency factor is considered in ACI which accounts for premature failure of the FRP jacket. In this, the hoop strain at failure (ε_{fe}) is limited to lesser of 0.004 and $0.75\varepsilon_{fu}$, this provision does not take into account the performance of FRP. On the other hand NCHRP does not have any provisions to define or limit the hoop strain at failure.

With regards to prediction of peak load value, ACI gave more accurate values compared to other guideline. At last, for the prediction of axial strain values also ACI seems to be more accurate.

The axial capacities of CFRP strengthened RC circular columns were obtained from FEA and they were compared to the values from the equations of ACI and NCHRP. Because of the reduction factors due to material properties or the loading conditions, the design guidelines were witnessed to be conservative.

6.2 Conclusions

Design approaches from two guidelines were presented and reviewed. The equations predicting the f'_{cc} and ε_{ccu} values were outlined. These values were compared to the results obtained from FEA.

With available knowledge and experimental evidences, further research should be carried on to confirm the basic assumptions made in the material models which would help to understand the controlling input parameters for analytical models. This would help to correctly calibrate the numerical models. Some of the suggestions would be concentrating the strain measurements along the perimeter of the FRP jacket, study on the longitudinal bar instability evident from outward deformation of the bar due to concrete dilation, study on the inclined wrapping, strain distribution of longitudinal bar, the contribution of the lateral reinforcement in the confinement and crack propagation detection. The available literature can be understood more properly if the performance and parameters which control the design are properly understood. To improve the cost efficiency of the wrapping scheme, study can also be made on partial wrapping, study can be made to find out the portions along the height of the column where the stresses are high and to confine the column on these portions. Study can be made on the decreasing branch of stress- strain curve of confined concrete to understand the ultimate strain in concrete and to define the point on stress-strain curve which will limit the cracking in the concrete.

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