JIMMA UNIVERSITY

SCHOOL OF GRADUATE STUDIES

JIMMA INSTITUTE OF TECHNOLOGY

FACULTY OF CIVIL AND ENVIRONMENTAL ENGINEERING

STRUCTURAL ENGINEERING STREAM

Finite Element Analysis of Carbon Fiber Reinforced Polymer Strengthened RC Beam Subjected to Bending and Torsion

By

Kalid Shifa Sabre

A Thesis Submitted to the School of Graduate Studies of Jimma University

In Partial Fulfillment of the Requirements for the Degree of Master

Of Science in Civil Engineering (Structural Engineering)

Mar,2022

Jimma, Ethiopia

JIMMA UNIVERSITY

SCHOOL OF GRADUATE STUDIES

JIMMA INSTITUTE OF TECHNOLOGY

FACULTY OF CIVIL AND ENVIRONMENTAL ENGINEERING

STRUCTURAL ENGINEERING STREAM

Finite Element Analysis of Carbon Fiber Reinforced Polymer Strengthened RC Beam Subjected to Bending and Torsion

By

Kalid Shifa Sabre

A Thesis Submitted to the School of Graduate Studies of Jimma University

In Partial Fulfillment of the Requirements for the Degree of Master

Of Science in Civil Engineering (Structural Engineering)

Main Advisor: Elmer C. Agon (Assoc. Prof.)

Co-Advisor: Mr. Ibrahim Kedir (MSc)

Mar, 2022

Jimma, Ethiopia

DECLARATION OF RESEARCH PROPOSAL

As a member of the examining board of the final MSc open defense, we certify that we have read and evaluated the thesis prepared by Kalid Shifa Sabre entitled: Finite Element Analysis of Carbon Fiber Reinforced Polymer Strengthened RC Beam Subjected to Bending and Torsion and recommended that it be accepted as fulfilling the thesis requirement for the degree of Master of Science in Structural Engineering.

Research proposal submitted by: -

1. Name of Chairman	Signature	Date
Abinet Alemseged	______________	_____________
2. Name of Main Advisor	Signature	Date
Elmer C. Agon, Assoc. Prof.	______________	_____________
3. Name of Co-Advisor	Signature	Date
Ibrahim Kedir (Eng.)	______________	_____________
4. Name of External Examiner	Signature	Date
DR	______________	_____________
5. Name of External Examiner	Signature	Date
Habtamu	______________	_____________

ABSTRACT

It is well known that the presence of properly unaccounted torsional moment reduces the load carrying capacity of RC members due to many reason, resulting in a torsion critical member. In order to avoid the brittle failure due to torsion, CFRP strengthening the member is one way. In order to effectively strengthen beams exhibiting flexure and torsional behaviors together it's important to identify factors that affect the performance of CFRP strengthened beams. A nonlinear study is carried out using ABACUS in order to investigate the effect of important parameters such as T/M ratio, amount, and distribution of transverse and longitudinal reinforcement.

For this study beam models are divided into two series. The first series contains nine (9) CFRP strengthened RC beams which are grouped into three based on relative amount and distribution of compressive and tensile reinforcements. The second series contains six (6) CFRP strengthened RC beams which are grouped into two based on the ratio of transversal to longitudinal reinforcement ratios. By comparing these results with the available experimental and numerical results the proposed model is found to be capable of analyzing CFRP strengthened beams to an acceptable accuracy.

The nonlinear finite element studies showed that the ultimate strength of torsion critical CFRP Strengthened members are greatly affected by relative amount of longitudinal reinforcement, ratio of transversal and longitudinal reinforcement, pattern of distribution of longitudinal reinforcement and ratio of torsion to bending moment. The Effect of torsion to bending moment ratio (T/M) on ultimate strength of torsion is clearly observed as the reinforcement amount and distribution changes. As T/M goes from 1 and 2 the ultimate torsional strength increases in 10.73% and T/M goes from 2 and 3 the ultimate torsional strength decreases by 6%. With the increment of longitudinal Compressive reinforcement, no significant torsional strength improvement is seen. With the increment of tensile reinforcement ultimate torsional strength in general is found increased. For λ=1 the ultimate torsional strength increases there is 4% improvement in strength for λ=2 there is 4% improvement in strength .for λ=3 ultimate torsional strength decreases with the increment of tensile reinforcement. It has been also observed that an increase in transverse to longitudinal reinforcement ratio (ρt / ρL) by 75.7% causes an increase in ultimate resisting torsional moment by about 5%, 2%, 8% for torsion moment ratio of λ=1, 2 and 3 respectively. The study also showed that increasing ratio of transverse to longitudinal reinforcement improves strength only when the increment is made by proportioning relative amount of transverse to longitudinal reinforcement ratio. Moreover, during strengthening of torsion critical members, attention should be given to the amount and distribution of reinforcements and the associated bending moment as they greatly affect the torsional strength improvement.

***Key words**: CFRP, Torsion to Bending moment ratio, transversal reinforcement, longitudinal reinforcement*

ACKNOWLEDGMENT

First of all, I would like to thank my creator Allah for helping me through the ups and downs to reach this place without his help nothing would happen.

My next sincere gratitude goes to for my main advisor Elmer C. Agon, Assoc. Prof. for guiding me to do this research Thesis and for his endless efforts to give whatever he knows. And also, I would like to thank my Co. advisor Ibrahim Kedir for his essential and helpful advice when this research proposal was prepared.

I am grateful to my family for their constant love and support. Thank you to my Dad, to my sisters Sadiya and Betula and to my beloved little brother keredin.Thanks to my friends Rihana, Adem, Fitsum and Mr Mitiku for your understanding and your never-ending encouragement and for always being there for me. Your support has meant more to me than you could possibly realize.

Finally, I want deeply to thank my mom, the lady who has always been there even when I did not want her to be there, I credit for ingraining in me the ways of logic which have become an intricate part of who I am and who I will be. I only hope to one day surpass her. Thank you mom for everything.

Table of Contents

LIST OF FIGURES

LIST OF TABLES

ACRONYMS

ACI	American Concrete Institute
FEM	Finite Element Method
FRP	Fiber Reinforced polymer
JiT	Jimma institute of Technology
RC	Reinforced Concrete
NSC	Normal Strength Concrete
CFRP	Carbon Fiber Reinforced polymer
AFRP	Aramid Fiber Reinforced polymer
CFRP	Glass Fiber Reinforced polymer
EBR	Externally bonded reinforcing
NSM	Near surface mounted
Mu	Ultimate strength in bending
Mub	Ultimate strength of the beams in combined bending and torsion
ρ	Reinforcement ratio
λ	Bending moment to torsional moment ratio
Ast%	Areas of tensile steels.
Asc%	Areas of compressive steels.
ρt%	Ratio of transverse (stirrups) reinforcement to the volume of the concrete
ρL%	Ratio of longitudinal reinforcement to the volume of the concrete
Mu	ultimate bending moment of resistance
Tu	ultimate torque

CHAPTER ONE

INTRODUCTION

1.1 Background of the study

Engineering structures are subjected to a variety of mechanical and environmental loading, as a result, structural members are forced to develop an internal resisting mechanism to counter the developed actions including shear force, bending moment and at times torsional moment. The mechanism of reinforced concrete (RC) member's resistance to flexure is well understood. Although a tremendous amount of work has been carried out on shear, a unified rational theory still remains elusive. When reinforced concrete members are not properly designed and detailed for torsion, an undesirable brittle mode of failure will be imminent, yet relatively little focus has been given to this problem. Torsional loadings can be separated into two basic categories: equilibrium torsion and compatibility torsion. When the torsional moment is required for the equilibrium of the structure, it is called equilibrium torsion. A balcony supported by plane frame could be an example of equilibrium torsion. When the torsional moment results from the compatibility of deformations between members meeting at a joint, it will be called compatibility torsion. Transverse beams supporting slabs with different spans might be exposed to compatibility torsion. It is well known that the presence of properly unaccounted torsional moment reduces the load carrying capacity of RC members, resulting in a torsion critical member [1]. RC members might be torsion critical due to different reasons. Some of the main reasons include: -

- Poor design or inappropriate detailing for torsion
- Change of design codes
- Change in the functionality of the structure
- Deterioration of concrete and corrosion of rebar
- Poor construction

The available mitigations for torsion critical structural members are either strengthening or demolishing the structural element. Often demolishing the members might not be feasible because of its economic repercussions, as a result, strengthening becomes the viable option. Structural members could be strengthened using different materials and techniques. In this thesis, the behavior of torsion critical RC beams strengthened by using an externally applied epoxy bonded carbon fiber reinforced polymers (CFRP) will be investigated. Although the material cost of the carbon fibers may be high, they are compensated by the lower cost of application and maintenance cost relative to the conventional strengthening schemes, such as member jacketing. Carbon fibers are characterized by having very high tensile strength, large deformation capacity, immunity to corrosion and high strength to weight ratio. As a result of their low weight, carbon fiber strip application is easier to apply in confined space and eliminates the need for scaffolding resulting in a reduction of labor costs. The stiffness of the fibers can also be tailored to the design requirements. Fiber reinforced polymers are practically available in different sizes and FRP geometry and dimensions [2] It is infrequent to get RC beams that are subjected to pure torsion; there will be associated flexural moment and shear force. In addition to acting external mechanical forces, one source of shear force and flexural moment might be the dead load supported by the beam. Although those internal forces act as a unit rather than separately, it is customary to study each action separately by assuming no interaction and superimpose the individual effect to get the total action effect. By following this path there are numerous studies conducted on carbon fiber wrapped RC beams subjected pure torsion.

There are many factors that affect the behavior of reinforced concrete beams strengthened. The most important factors affecting the behavior of reinforced concrete members subjected to combined bending and torsion are T/M ratio, amount and distribution of transverse and longitudinal reinforcement, cross section shape, and concrete strength [3].

The primary goal of this paper is to investigate and describe the behavior and ultimate strength of beams externally reinforced with fiber reinforced polymer (FRP) laminates using finite elements method adopted by ABAQUS. Nonlinear finite element is used to investigate relative amount of longitudinal reinforcement, ratio of transversal and longitudinal reinforcement, pattern of distribution of longitudinal reinforcement and ratio of torsion to bending moment on the ultimate strength of a member.

1.2 Statement of the problem

It is well known that due to many reason the presence of properly unaccounted torsional moment reduces the load carrying capacity of RC members resulting in a torsion critical member.in some situation the only available mitigations for such torsion critical structural members would be strengthening. The strength and behavior of strengthened reinforced concrete rectangular sections subjected to bending, shear and torsional moments have individually been extensively studied in the past both theoretically and experimentally. However, the performance and behavior of strengthened members under combined effect of torsional and flexural loading has hardly been studied.

In order to strengthen beam exhibiting flexure and torsional behaviors together, different studies suggest full and U wrapping scheme of CFRP laminates although the two differ on practical feasibility for monolithically casted structures. Therefore, to determine the performance and effectiveness of a CFRP U wrap strengthening scheme for improving ultimate torsional strength of Reinforced concrete rectangular sections under combined effect of torsion and flexure needs to be studied well.

1.3 Objectives of the study

1.3.1 General objective

The general objective of this study was assessing the behavior and performance of RC rectangular beams strengthened with externally bonded Carbon Fiber Polymer (CFRP) subjected to combined flexure and torsion.

1.3.2 Specific objectives

- To investigate the effect of torsion to flexure ratio on the torsional capacity of torsion critical CFRP strengthened beams.
- To check the effect of varying Longitudinal Tensile steel amount on torsional strength of CFRP strengthened beams.
- To check the effect of varying Longitudinal Compressive steel on torsional strength of CFRP strengthened beams.
- To check the effect of varying ratio of transversal to longitudinal steel amount on the Torsional strength of CFRP strengthened beams.

1.4 Significance of the study

With the increasing interest in a philosophy of design based on limit states, it is desirable to consider the behavior of a structure under different combined external action. The research focuses on filling the gaps that have not yet been investigated in the literature which can be used for structural engineer’s practical guidelines for new design and in upgrading strength of existing structural members as well.

1.5 Scope and limitation of the study

This research was done by using commercially available software ABAQUS and excel. The study is limited to small beams of cross section 200 mm x 2000 mm and the size factor has not been considered. The applied torque to bending moment ratio varies from 1 to 3. The percentage of tensile reinforcement varies from 0.2512 to 0.5024, compressive reinforcement -from 0.2512 to 0.5024 and ratio of transverse to the longitudinal reinforcement from 0.5 to 1. Influence of shear stirrups is considered constant for all for series 1 and varied for series 2. Only one type of concrete grade is used in the study and its compressive strength of concrete is 36.54 MPa. Torque capacity of the beams is studied in combination with bending moment. The study will be devoted to see the CFRP strengthened simply supported beam under combined bending and torsion

CHAPTER TWO

REVIEW OF RELATED LITERATURE

2.1 General Review on Methods of Strengthening of RC Beam

Different methods of structural strengthening (retrofitting) techniques have been developed over the years such as external bonding of steel plates, glass fiber reinforced plastic (CFRP), fiber reinforced polymer (FRP) sheets, external prestressing, carbon fiber wrapping, external bar reinforcement, and very recently improved external (bars) reinforcement techniques.

In 90s, steel plating was considered as a most effective way to strengthen an RC beam, however steel plating demands high cost and difficult in application, exhibits less fatigue resistance, may easily corrode, and increases dead weight of the structure. On the other hand, FRP has many advantages in terms of ease in application, high strength to weight ratio, non-corrosiveness, non-magnetic characteristic. These characteristics make FRP a most effective material for repair and rehabilitation of a deficient RC structure [4]. Trend of research potential on FRP has been arisen since last many years, but its applications are still unexplored. Strengthening and retrofitting of existing structures using externally bonded FRP is one of the first applications of FRP introduced in civil engineering. In 1980s, several researchers initiated using FRP in civil engineering applications as a separate research domain to explore properties of FRP and highlighted typically three main fibrous materials as glass, aramid, and carbon to strengthen structural members [5]. Carbon fiber is usually manufactured in two categories i.e., high modulus and high strength. Glass fiber is produced in two forms i.e., E-glass and S-glass.

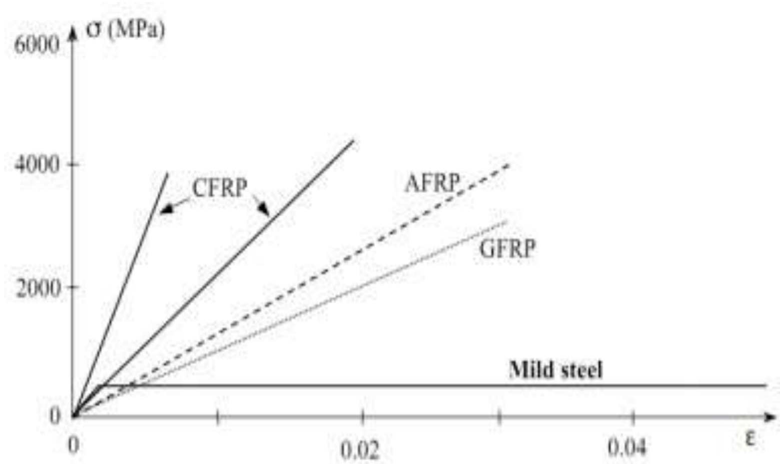

Figure 2.1 Uniaxial tension stress-strain diagrams [6]

General behavior of FRP in comparison to steel under tensile stresses, stress-strain relations has been shown in Fig 2.1, which shows that stiffness of CFRP is higher than CFRP and AFRP. Whereas CFRP and CFRP are used in high level of reinforced concrete strengthening applications. Some of typical material properties of FRP carbon, glass, and aramid are shown in Table 2.1

Table 2.1 Typical properties for the different FRP [7]

Material	Tensile Strength (MPa)	Modulus of Elasticity (GPa)	Density (Kg/m^3)	Modulus of elasticity to density ratio(Mm^2/s^2)
Carbon	2200-5600	240-830	1800-2200	130-380
Aramid	2400-3600	130-160	1400-1500	90-110
Glass	3400-4800	70-90	2200-2500	31-33
Steel	280-1900	190-210	7900	24-27

2.2 Wrapping Schemes

Fiber-reinforced polymer (FRP) materials have been used extensively as an alternative reinforcement for new construction, as well as for strengthening and repairing existing structures, and their use has increased in recent years [8]. For the purpose of strengthening of concrete beams, FRP materials can be applied by the following two major techniques: externally bonded FRP sheets and strips applied to the external faces of the elements, and near-surface mounted (NSM), which involves the installation of CFRP into slits on the concrete cover of the beams' lateral faces.

2.2.1 Externally bonded reinforcing (EBR)

Many studies have been carried out to examine the use of externally bonded FRP and its effectiveness in strengthening concrete structures. The FRP materials are typically applied to the concrete surface using a bonding agent after adequate surface preparation of the concrete, typically involving sandblasting, water jetting, and the application of a suitable primer. Once applied, depending on the bond, several days of curing are typically required to achieve the full bond strength of the system [9]. Many FRP configurations have been used to evaluate the contributions of external transverse or longitudinal FRP reinforcements applied to beams with rectangular, box, spandrel, and flanged cross-sections. The configurations can be summarized as follows:

(1) Full wrapping (all faces wrapped) with vertical strips or along the entire length as in Figure 1 (a), (c), (f), (i), (l) and (o): Continuous sheets or vertical strips (90° strips) with various dimensions and spacing's have been completely wrapped around the cross section of beams excluding spandrel beams.

(2) U-jacketed (three faces wrapped normally) with vertical strips or along the entire length as in Figure 1 (b),(d),(j), (k), (m), and(n): Continuous sheets or vertical strips (U strips) with various dimensions and spacing's have been used by bonding them on the bottom and both vertical sides of the rectangular, box, and spandrel beams, and the web of T beams, with or without extended FRP anchorages.

(3) Inclined FRP strips as in Figure 1 (g) and (h): 45° FRP strips have been used by bonding them on one side of the beam or in a spiral around the beam with rectangular cross-section beams

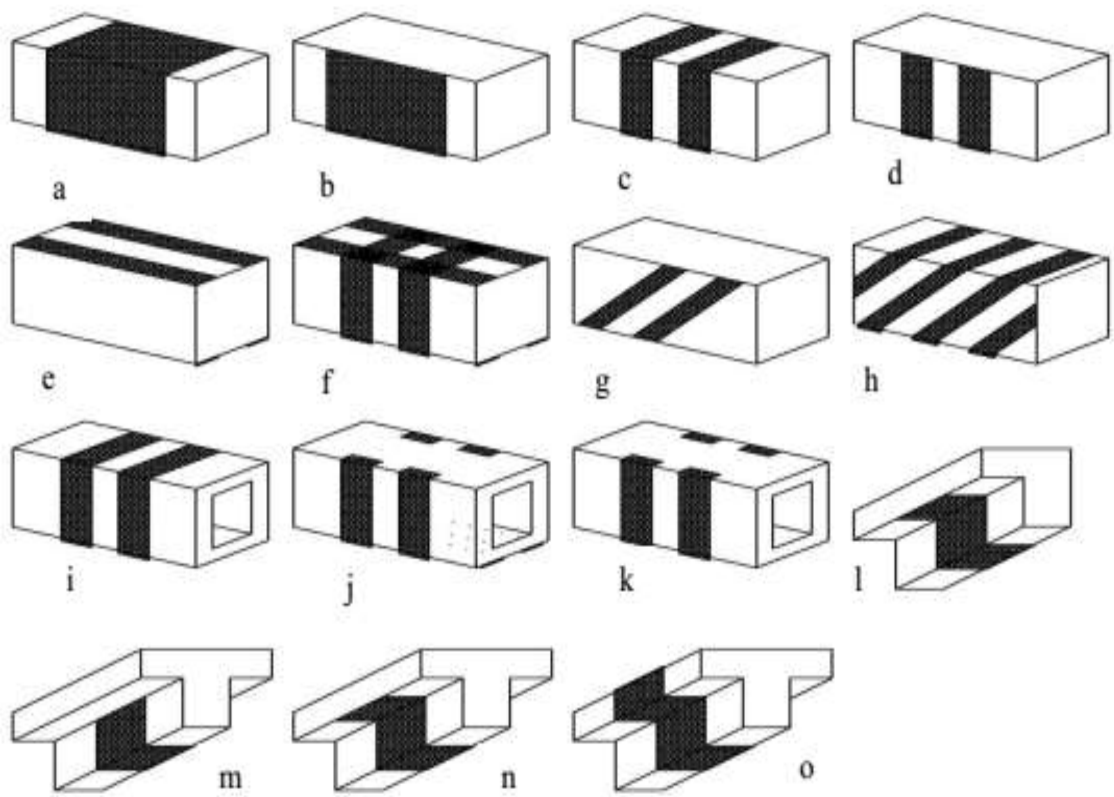

Figure 2.2 Wrapping schemes for torsion strengthening [11]

2.2.2 Near Surface Mounted (NSM).

Early de-bonding has become the major issue in the EBR FRP strengthening technique. To reduce these problems, the near-surface mounted (NSM) technique [10]. Provides greater resistance to debonding. It is used to strengthen beams by installing CFRP bars into grooves cut in the concrete cover of the beam lateral faces using epoxy adhesive as a bonding material [10]. Many studies have indicated that the NSM technique is feasible and beam strength capacity could be increased significantly compared with EBR application.

2.3 Literature Review on Strengthening of RC Beam

2.3.1 Experimental and Analytical Studies on Torsional Strengthening

Even though it recognized the limited amount of research and testing on FRP-strengthened concrete elements in torsion**,** according to fib bulletin [11], design procedures for torsional strengthening can follow a similar approach to that of shear strengthening with minor alteration. The feasibility of FRP for the strengthening of torsional behavior has been investigated by many researchers and most of the studies are conducted in the last two decade.

Panchakarma et al. [12] conducted analytical and experimental work on torsional strengthening of RC members. They considered different variables including the glass fiber Orientation, the number of beam faces strengthened (three or four), the effect of the number of FRP plies used, and the influence of anchors in their study. Their investigation showed a very promising result on the feasibility of using FRP for torsion critical members.

Ronagh et al. [13] experimentally investigated three RC concrete beams. The RC beams were intentionally designed to be torsion critical. Two of the three beams were reinforced with CFRP. The pure torsion test shows that the torsional strength of beams strengthened with fibers was almost twice than that of the control beam.

Ameli et al. [14] conducted pure torsion test on 12 reinforced concrete beams wrapped by carbon and glass fibers. Different configurations were used for the FRPs, and the torque-twist angle paths of the beams were recorded to failure. The experimental result showed a significant enhancement in the ultimate torque with 87 and 143 percent increase for one and two layers of carbon fiber wrapping respectively.

Salom et al. [15] experimentally and analytically studied six identical spandrel beams. The beams were tested with pure torsion. The specimens include two baseline specimens with four retrofitted sample for comparison. The variables considered in the study include fiber orientation and effects of a laminate anchoring system. The experiments showed that the CFRP could increase the torsional capacity of concrete beams by more than 70%.

Rashidi et al. [16] experimentally studied effect of reinforcement type on torsion strength of concrete beam. His experiments focus the role of stirrups and longitudinal reinforcement on torsion strength. Four beam test samples have been tested with the same length and concrete mix design.

The reinforcement of this samples has been different ranging from without reinforcement to complete reinforcement. The experimental results show that the ductility factor increases with increasing percentage reinforcement. The torsional strength and ductility of the sample with transverse and longitudinal bars have been increased 95% and 50% respectively in comparison with sample without reinforcement. The transverse bars play an important role in torsional strength of Reinforced Concrete Beams compared to longitudinal bars. It should be also noted that transverse bars or longitudinal bars lonely would not be able to increase the torsional strength of RC beams and both of them can be essential for having a good torsional behavior in reinforced concrete beams.

Mohammadizadeh et al. [17] tested two rectangular cross-section strengthened beams with U-jacket strips using CFRP with different steel reinforcement ratios (1.56%, and 2.13%). It was claimed that the use of various steel stirrup ratios had a small effect on the CFRP contribution.

2.3.2 Experimental and Analytical Studies on flexural strengthening

Many studies have been undertaken on ultimate strengthening of reinforced concrete (RC) beams by externally bonding fiber reinforced polymer (FRP) composites. RC Beam should strengthen to efficiently increase ultimate strength of the beam. Also, ductility is main concern. CFRP have being effectively used to strengthen RC beam under flexural. Several studies have been conducted to provide a better solution to strengthen RC beam. Experimental studies shows that number of CFRP layer increase ultimate load carrying capacity, yield loads, flexural stiffness of the RC beam, but the failure observed was not ductile due to delamination of layer [18].

Esfahani MR. et al. [19] experimentally studied flexural behavior of reinforced concrete beams strengthened using Carbon Fiber Reinforced Polymers (CFRP) sheets. They manufactured total twelve concrete beam specimens with dimensions of 150 mm width, 200 mm height, and 2000 mm length. They designed beam sections with three different reinforcing ratios, and they used as longitudinal tensile reinforcement in specimens. Nine specimens were strengthened CFRP sheets and three control specimens. They concluded that ultimate strength and stiffness of the strengthened beams increased compared to the control specimens. Test results showed that the effect of CFRP sheets in increasing the ultimate strength of beams with small reinforcing bar ratio values compared to maximum code value. In the large reinforcement bar ratio failure of the CFRP sheet strengthened beams occurred with adequate ductility. The result of their experiment is shown in following fig.2.3. The horizontal axis represents ρ/ρb in which ρ is the reinforcement ratio and ρb is the balanced reinforcement ratio. The vertical axis represents Pu/Pcon which describes the performance of strengthening, in which Pu and Pcont represent the ultimate capacity of strengthened specimen and control beam.

Fig 2.3 it is clearly shown that by increasing ρ/ρb the performance of strengthening with FRP decreases. It can be observed that for smaller amount of reinforcement ratios, the capacity of strengthened beams can exceed two times the capacity of their corresponding control beams

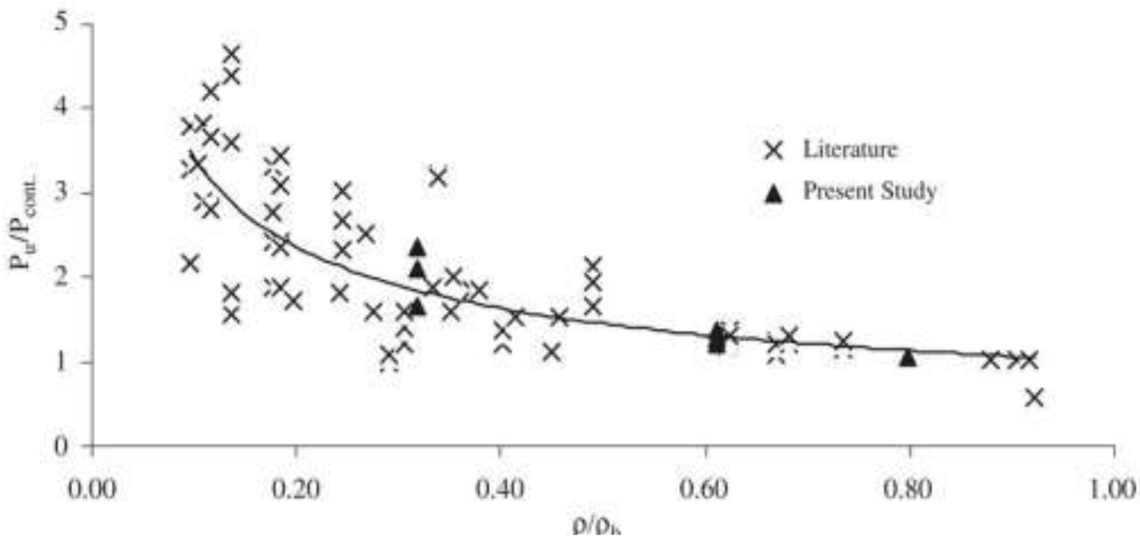

Figure 2.3 The ultimate capacity vs reinforcement ratio [19]

Hashemi SH. et al. [18] investigated the effectiveness of externally bonded CFRP sheets to increase the ultimate strength of reinforced high strength concrete (HSC) beams. The main test variables considered in the present study include the FRP sheet layers and tensile bars. The FRP sheet layers varies from 0 to 4 and the bar reinforcement ratio varies from 1.2 % to 2.4 %. Four-point bending flexural tests on six concrete beams, and they observed flexural tests to complete failure on concrete beam. So, these strengthened with different arrangement of CFRP sheets were conducted. Then they checked three-dimensional nonlinear finite element (FE) models by ANSYS, and they examined the behavior of the test beams. Then they also checked the strength and ductility of the beams as the number of FRP layers and tensile reinforcement bar ratio changed. Finally, authors concluded that the energy ductility value is about two times more than the displacement ductility values. They also found that the crack patterns in the reinforced high strength concrete beams was also presented.

Dong, et al. [20] experimentally studied Structural behavior of RC beams with external flexural and flexural shear strengthening by FRP sheets. They tested total seven concrete beams out of six were ultimate strengthened with each single layer or two layers of CFRP sheets and one control beam. They concluded that the increase on the overall ultimate strength of the CFRP strengthened beams varies between 41% and 125% over the control beam and on the shear capacity of the CFRP or CFRP strengthened beams between 31% and 74%. They found that control development of cracks and increase ductility of the beams. They also theoretically predicted the ultimate strength and the ultimate shear carrying capacity which show reasonably good correlation to experimental results.

El-Gamal et al. [21] carried out experimental study on behavior of reinforced concrete (RC) beams strengthened in flexure with near surface mounted (NSM) technique using glass and carbon fiber reinforced polymers (CFRP & CFRP). A total of 10 full scale reinforced concrete beams rectangular cross section 200 × 300× 2760 mm were constructed and strengthened in flexure with FRPs. They were included four parameters: technique used (NSM or Hybrid), type of FRP used (carbon or glass), amount of FRP used, and steel reinforcement ratio. They tested four point bending set-up was all beams. The test results included ultimate capacity, strains, cracking, deflection, and mode of failure. They concluded that all strengthened beam increase in the capacity reaching between 31 and 133% compared with the reference beams. Authors also found that the NSM-CFRP strengthened beams excellent ultimate capacities than the NSM-CFRP beams but they showed less ductile behavior. They concluded that all strengthened beam increase in the capacity reaching between 31 and 133% compared with the reference beams. Authors also found that the NSM-CFRP strengthened beams excellent ultimate capacities than the NSM-CFRP beams but they showed less ductile behavior. They concluded that all strengthened beam increase in the capacity reaching between 31 and 133% compared with the reference beams. Authors also found that the NSM-CFRP strengthened beams excellent ultimate capacities than the NSM-CFRP beams but they showed less ductile behavior. The NSM-CFRP strengthened beam found better ductile behavior with high deflection values at ultimate load. They concluded that all strengthened beam increase in the capacity reaching between 31 and 133% compared with the reference beams. Authors also found that the NSM-CFRP strengthened beams excellent ultimate capacities than the NSM-CFRP beams but they showed less ductile behavior. Authors also found that the NSM-CFRP strengthened beams excellent ultimate capacities than the NSM-CFRP beams but they showed less ductile behavior.

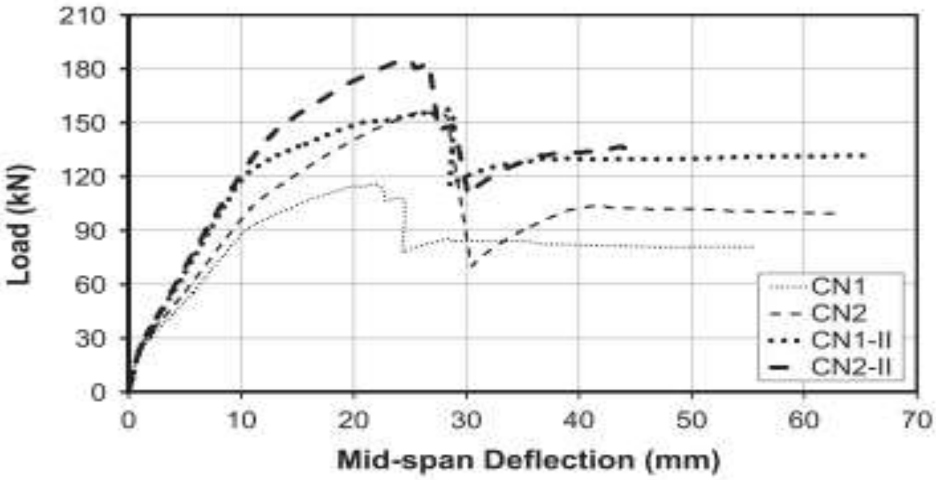

Figure 2.3 Effect of steel reinforcement ratios [18]

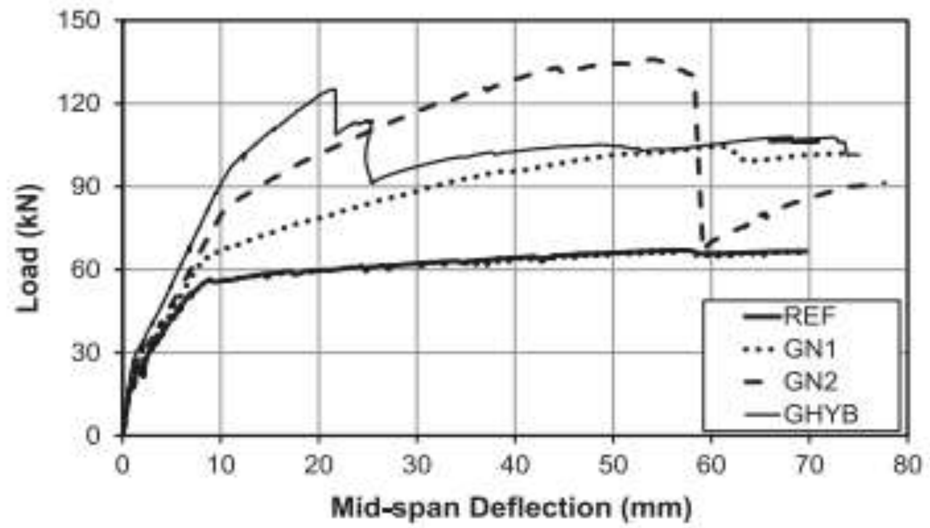

Figure 2.4 Effect of technique used (CFRP beams) [18]

2.3.3 Experimental and Analytical Studies on Flexural and torsional Strengthening

It is agreed that, loading on reinforced concrete beams, especially spandrel one, is mainly combined of bending moment and shear force as well minor torsional moment.

Despite bending moment is always decisive for alike combination of loading [20-21], however, load points of action and positions need to be observed its effects to assurance corresponded structure's performance and efficiency under a certain distribution of loading. Almost all of previous research's indicated decrease in strength and stiffness of beams tested under combined shear and bending stresses propagated from eccentric loading. Some researchers determined ratios of bending moment/torsional moment (λ) in which bending moment can be dominant on the beam structural behavior and failure mode. The ratio of dominant bending moment via precedes research's is ($\lambda \geq 2.5$) [19], ($\lambda \geq 2.0$) [20] and ($\lambda > 1.0$) [21] where beams configurations and test setup were different in each research respectively.

Tudu [22] conducted an experimental study to observe the effect of CFRP strengthened RC beam under combined effect of torsion and bending. Study concluded the same results as previous studies revealed that full wrap is more effective strengthening scheme for torsion strengthening whereas 45° wrap are more suitable than 90° wraps.

Jariwala et al. [23] carried out an experimental study on CFRP laminate beams. The beams were tested under combined torsion and bending. The results summarized that the full transverse wraps give high torsional moment resistance than other wrapping schemes. On the other hand, vertical wraps were less effective than diagonal strip wrapping, which exhibited better performance in torsion resistance.

Santhakumar et al. [24] presented the numerical study on unretrofitted and retrofitted reinforced concrete beams subjected to combined bending and torsion. Different ratios between twisting moment and bending moment are considered. The finite elements adopted by ANSYS are used for this study. For the purpose of validation of the finite element model developed, the numerical study is first carried out on the un-retrofitted reinforced concrete beams that were experimentally tested and reported in the literature. Then the study has been extended for the same reinforced concrete beams retrofitted with carbon fiber reinforced plastic composites with ±45and 0/90 fiber orientations. The present study reveals that the CFRP composites with ±45 fiber orientations are more effective in retrofitting the RC beams subjected to combined bending and torsion for higher torque to moment ratios. From the Figure 2.4, it is seen that the ultimate strength of the beam under combined bending and torsion decreases as Ø increases. The percentage reduction in the ultimate strength of the beams C, R+ and R# are found to be 43.2, 28.96 and 22.4 respectively.

Al-Rousan et.al [35] investigated the behavior of simply supported RC beams strengthened using CFRP and subjected to combined bending and torsion using Nonlinear Finite Element Analysis (NLFEA). Twenty-six models have been constructed and divided into six groups to scrutinize the effect of clear span to depth ratio; CFRP length; CFRP strip spacing; and CFRP depth. The results showed that the increase in the clear span to depth ratio as well as length of CFRP leads to a notable increase in the ductility and decreases the ultimate load. The models with zero spacing CFRP strips

(Fully) showed a higher considerable effect than the models with strips wrapping. Furthermore, this enhancement was the highest for group six which contains the models with the highest CFRP depth.

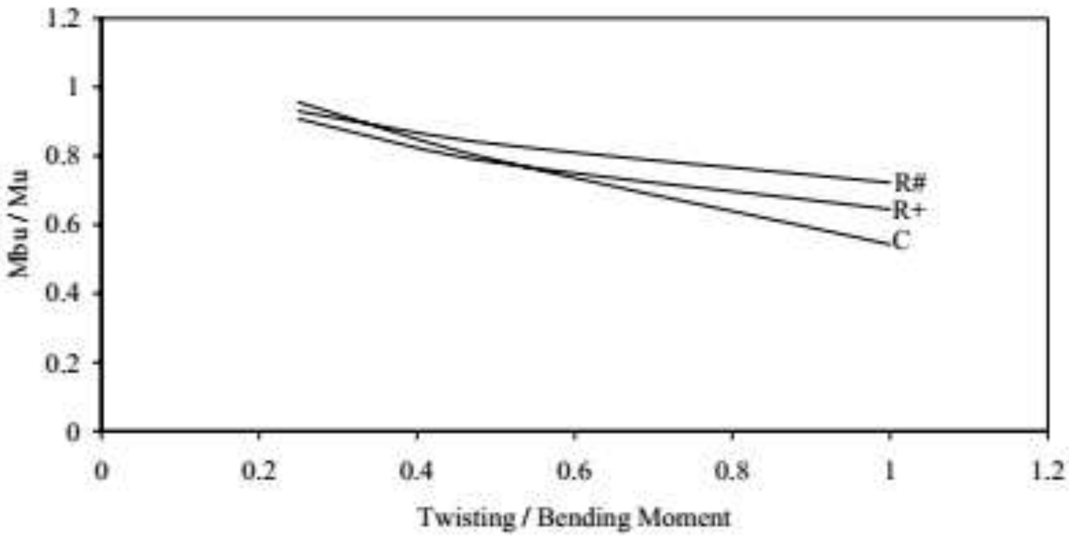

Figure 2.5 Ultimate strength of the beam [24]

2.3.4 Experimental and Analytical Studies on Strength of beam under combined torsion and flexural loading

A lot of researchers have conducted an investigation on different parameters that influence the torsional and flexural behavior of RC members.

Ersoy et al. [25] tested 25 small-scale reinforced concrete L beams without stirrups to evaluate the effects of different parameters including longitudinal reinforcement ratio, flange width and load eccentricity in the torsional resistance. They concluded that longitudinal steel ratio has a considerable effect on the torsional strength. This effect decreases with increasing eccentricity. Also, based on their results the load eccentricity has a significant influence in the torsional behavior of the test specimens. In another experimental study, Aryal [26] found that increasing the longitudinal tensile reinforcement would not change the torque values. However, with the increment of longitudinal compressive reinforcements, an increase in torque values at different points was observed. In addition, his results described the effect of longitudinal tensile and compressive reinforcements in improving the torsional rigidity at cracking and ultimate points depending on the amount of the torque to bending moment ratio. His tests also indicated a moderate increase in the torsional ductility factor with increasing the longitudinal compressive reinforcements. Victor and Ferguson [27] suggested an interaction relationship of torsion and moment in RC beams without stirrups in the absence of flexural shear. Mizra et al. [28] also investigated the bending-torsion interaction behavior of concrete beam reinforced only with longitudinal reinforcement. Their experimental tests under pure torsion indicated that increasing the longitudinal reinforcements would improve the initial cracking and ultimate strength in interaction curve by approximately 15% and the twist angle was almost doubled. They also reported a linear brittle failure for unreinforced beams up to failure point in which the ultimate normal stress of concrete corresponded to the concrete rupture modulus. Based on their test results, the behavior of reinforced beam before initial cracking was identical to the unreinforced beam. After cracking, however, the reinforced specimens showed a somewhat ductile behavior with a reduction in torsional rigidity. Using past experimental tests, Hsu [29] presented a nondimensional interaction surface for combined shear, torsion, and bending in beams without stirrups. They have also suggested a simple and conventional design criterion for beams reinforced with longitudinal reinforcement only under combined actions.

In an experimental and analytical study, Ramakrishnan et al. [30] developed a relation between torque and twist of rectangular RC beams with and without transverse reinforcements under pure torsion. The ultimate strength of RC beams containing only longitudinal reinforcement under combined bending and torsion was also evaluated by Gesund et al. [31] using a series of experimental testing. They also developed a theoretical model to verify their test results. Based on their experimental outcomes, they reported the predominant effect of dowel action of longitudinal reinforcement in resisting the torsion in RC beams without transverse reinforcement.

Nonlinear finite element (FE) analysis has also been implemented extensively to scrutinize the behavior of reinforced concrete beams under torsion. Mahmood [32] has performed a nonlinear FE study to investigate the effects of different parameters including the beam’s length and torsional reinforcements in torsional strength, and behavior of beam before and after cracking. Recently, Mostofinejad et al. [33] developed a numerical model using the concept of smeared cracking model in ANSYS (2005) to investigate the behavior of RC beams under torsion. Comparison of their FE results with the experimental outcomes, endorsed the accuracy of numerical analysis in predicting the cracking pattern and fracture torque. The smeared cracking model has also been used by Lisantono [34] for nonlinear FE analysis of RC hybrid deep T beam with opening. The obtained torque-twist angle curve from the nonlinear FE analysis could accurately estimate experimental linear behavior of deep T beam before cracking. After cracking, however, the nonlinear curve obtained from the FE analysis was stiffer than the experimental results.

2.3.5 CRITICAL OBSERVATION FROM THE LITERATURE

From the above literature review it is clear that the effect of torsional moment to bending moment to ratio, amount, and pattern of steel on the behavior of concrete beams under combined flexure and torsion are clearly seen.it is also shown that different strengthening schemes were used to increase ultimate strength of beam under combined flexure and torsion loading. However, none of the above models predicted the effect of longitudinal and transversal steel individually or longitudinal steel along with transverse steel on the behavior of CFRP strengthened beams for combined flexure and torsion loading at ultimate strength stage.

CHAPTER THREE

RESEARCH METHODOLOGY

3.1 General Overview

This chapter presents and describes the approaches and techniques that the researcher uses to collect data and analyze the research problem. This includes the research design, sample size and selection, sampling techniques and procedure, data collection methods, data quality control (validity and reliability), procedure of data collection, data analysis

3.2 Research design

The research design will be based on an inductive sampling selection process in terms of which a relevant factor, which are essential for the comparative study of CFRP strengthened beam for combined action of bending and torsion by using finite element analysis of ABAQUS. This research is a systematic investigation to find answer to the problem. On the other hand, it is a process for collecting, analyzing, and interpreting information to provide a recommendation to the research findings. After comprehensively, organizing literature review of different previous published research, designate the comparative study of CFRP strengthened beam on combined bending and torsion with a previous experimental result for different parameters. From framing layout all the way through to detail drawing production, ABAQUS integrates every aspect of the engineering design process in one easy and intuitive environment. ABAQUS provides unmatched benefits to the engineer with its truly unique combination of power, comprehensive capabilities, and ease-of use. A selection of parameters was accessible to analysis the influence of ultimate strength and deflection of CFRP strengthened beam. In this study CFRP strengthened beam from literature review were analyzed for software validation using finite element analysis tool ABAQUS.

3.3 Study variables

3.3.1 Dependent variables

- ❖ Torsional performance

3.3.2 Independent variables

- ❖ Torsional moment to bending moment ratio

- ❖ Areas of tensile steels
- ❖ Areas of compressive steels
- ❖ Ratio of transverse to the longitudinal reinforcement

3.3.3 Beam Model

The specimen was selected based on the above variables. The key parametric study are longitudinal steel, transversal steel, ratio of transversal steel to longitudinal steel and ratio of torsional moment to bending moment. For this study beam model are divided into two series. The first series contains nine (9) CFRP strengthened RC beams which are grouped into three based on relative amount and distribution of compressive and tensile reinforcements. The second series contains six (6) CFRP strengthened RC beams which are grouped into two based on the ratio of transverse to longitudinal reinforcement ratios. For series 1 amount of longitudinal reinforcement is only varied at top and bottom of the cross section while, for series 2 the longitudinal reinforcement is equally distributed over the perimeter of the cross section. For the entire sample, the load applied on the CFRP strengthened beam were a two-point load at different eccentric locations of the beam span. As it can be seen from Table 4, by fixing other dimensions of the proposed test beam, for different torsional to flexure moment ratios the required length of the lever arm will vary considerably. In order to force failure in the mid zone of the tested beam, end zones of (300 mm) long on each end of the beam were reinforced with (Φ 8 mm) stirrups spaced at (40 mm) on centers.

All the beams were designed to fail in torsion. Under certain ratios of loading and certain arrangements of reinforcement failure may occur before both the longitudinal and transverse Steel have yielded. Failure before yield of the longitudinal steel is possible if, the loading is such that a premature shear failure occurs, the amount of longitudinal steel is out of proportion to the amount of transverse reinforcement, The percentage of longitudinal reinforcement is excessive and General Crushing [36], [37], [38] In order to avoid failure of the beams at torsional and flexural cracking load, each beam was designed based on ACI 318 [1] requirement to have a minimum longitudinal and transversal steel reinforcements to the volume of the concrete. The percentage of reinforcement provided in the beam was slightly higher than the minimum required [8] to maintain the integrity of the beam beyond cracking.

Table 3.1 The characteristics of series 1

Series	SN	design	Cross Sectional Area		Longitudinal Reinforcement		Stirrup		(ρt/ρL) %	Wrapping scheme	λ
			B (mm)	D (mm)	Ast%	Asc%	Dia	ρt%			
1	1	A1	200	200	0.2512	0.2512	8	0.5024	100.0	U-Wrap	1
	2	A2	200	200	0.2512	0.2512	8	0.5024	100.0		2
	3	A3	200	200	0.2512	0.2512	8	0.5024	100.0		3
	4	B1	200	200	0.5024	0.2512	8	0.5024	66.7		1
	5	B2	200	200	0.5024	0.2512	8	0.5024	66.7		2
	6	B3	200	200	0.5024	0.2512	8	0.5024	66.7		3
	7	C1	200	200	0.5024	0.5024	8	0.5024	50.0		1
	8	C2	200	200	0.5024	0.5024	8	0.5024	50.0		2
	9	C3	200	200	0.5024	0.5024	8	0.5024	50.0		3

Table 3.2 The characteristics of series 2

Series	SN	design	Cross Sectional Area		Longitudinal Reinforcement			Stirrup			(ρt/ρL) %	Wrapping scheme	λ
			B (mm)	D (mm)	Dia	No	ρL% (Total)	Dia	S	ρt%			
2	1	D1	200	200	8	8	1.005	6	70	0.204	20.33	U-Wrap	1
	2	D2	200	200	8	8	1.005	6	70	0.204	20.33		2
	3	D3	200	200	8	8	1.005	6	70	0.204	20.33		3
	4	E1	200	200	8	8	1.005	8	70	0.359	35.71		1
	5	E2	200	200	8	8	1.005	8	70	0.359	35.71		2
	6	E3	200	200	8	8	1.005	8	70	0.359	35.71		3

Note: Ast, Asc - areas of tensile and compressive steels.

Ast%-Areas of tensile steels.

Asc%-Areas of compressive steels.

ρt%-Ratio of transverse (stirrups) reinforcement to the volume of the concrete

ρL%-Ratio of longitudinal reinforcement to the volume of the concrete

The percentage of longitudinal reinforcements is calculated from the overall dimension of the beam.

3.3.4 OVERVIEW OF TORSION DESIGN PROVISIONS

ACI 318-194, are theoretically based on the space truss model. In this formulation, torsion is assumed to be carried by shear stresses which circulate around the member's perimeter, which in turn are resisted by tensile stresses in the longitudinal and transverse reinforcement and diagonal fields of compression in the concrete. Historically, the space truss approaches are based on the design provisions described by Collins [39].The ACI 318-19, Torsion Design provision mainly contains the following five main components:

1. A threshold torsion limit, T_{th} below which the effects of torsion may be neglected
2. Requirements for minimum reinforcement
3. An upper limit on the permissible shear and torsion which can be resisted by the member
4. Equations to calculate the nominal torsional strength of the member
5. Various requirements or equations which describe how torsion interacts with moment and shear

3.3.5 ACI 318-19 design provisions

1. Threshold torsion – In ACI 318-19, torsional effects may be neglected if the magnitude of the torsion, Tu, is less than the threshold torsion Tth. For members with a solid cross section which are not subjected to axial force, Tth is:

$$T_{th} = \phi\lambda\sqrt{f_c'}\left(\frac{A_{cp}^2}{p_{cp}}\right)\sqrt{1+\frac{f_{pc}}{4\lambda\sqrt{f_c'}}} \quad (1)$$

Where pcp is the outside perimeter of the cross section, Acp is the area enclosed by pcp, fc' is the specified concrete cylinder compressive strength in psi, fpc is the compressive stress in the concrete at the centroid of the cross section after accounting for all pre stress losses in psi, λ is a factor to account for low density concrete taken here as 1.0 and ϕis a reduction factor for shear and torsion equal to 0.75

2. Minimum reinforcement requirements – The minimum quantity of closed transverse reinforcement which must be provided if torsion is considered is:

$$\left(\frac{A_v + 2A_t}{s}\right)_{min} = \max\begin{cases} 0.75\sqrt{f_c'}\,\dfrac{b_w}{f_{y,t}} \\ 50\,\dfrac{b_w}{f_{y,t}} \end{cases} \tag{2}$$

Where *Av* is the area of shear reinforcement, *At* is the area of one leg of closed transverse torsion reinforcement, *s* is the spacing of the transverse reinforcement, *fyt* is the yield strength of the transverse reinforcement in psi and *bw* is the minimum effective web width.

The minimum quantity of longitudinal torsional reinforcement which must be provided is calculated using Eq. (3). This reinforcement must be uniformly distributed around the inside perimeter of the transverse reinforcement and be spaced less than 305 mm (12 in) apart. The minimum quantity of longitudinal torsional reinforcement which must be provided is calculated using Eq. (3). This reinforcement must be uniformly distributed around the inside perimeter of the transverse reinforcement and be spaced less than 305 mm (12 in) apart

$$A_{l,min} = \min\begin{cases} \dfrac{5\sqrt{f_c'}A_{cp}}{f_{y,l}} - \left(\dfrac{A_t}{s}\right)p_h\dfrac{f_{y,t}}{f_{y,l}} \\ \dfrac{5\sqrt{f_c'}A_{cp}}{f_{y,l}} - \left(\dfrac{25b_w}{f_{y,t}}\right)p_h\dfrac{f_{y,t}}{f_{y,l}} \end{cases} \tag{3}$$

3. Upper limit on permissible shear and torsion – To control cracking and avoid crushing of the cross section prior to yielding of the reinforcement, the magnitude of the applied shear force *Vu* and torsion *Tu* is limited by the following equation for solid sections:

$$\sqrt{\left(\frac{V_u}{b_w d}\right)^2 + \left(\frac{T_u p_h}{1.7A_{oh}^2}\right)^2} \le \phi\left(\frac{V_c}{b_w d} + 8\sqrt{f_c'}\right) \tag{4}$$

Here *Vc* is the shear strength attributed to the concrete, *bw* is the minimum effective web width, *d* is the effective depth of the member and *Aoh* is the area enclosed by the centerline of the closed torsion reinforcement

4. Nominal torsional strength – The nominal torsional resistance *Tn* shall exceed the factored demand *Tu* and is calculated as follows:

$$\phi T_n \geq T_u \tag{6}$$

$$T_n = \min \begin{cases} 2A_o \dfrac{A_t f_{y,t}}{s} \cot\theta \\ 2A_o \dfrac{A_l f_{y,l}}{p_h} \tan\theta \end{cases} \tag{7}$$

$$A_o = 0.85 A_{oh} \tag{8}$$

Where *Ao* is the area enclosed by the shear flow path and θ is the angle of diagonal compressive stresses in the concrete. Although ACI 318-19 permits the use of θ ranging from 30° to 60°,

5. Interaction with moment and shear – Under combined moment and torsion, a member may fail due to yielding of the longitudinal flexural reinforcement, since this steel is required to carry the tension arising from both the torsion and bending moment. When analyzing a member subjected to moment and torsion which fails in this manner, the torsional resistance may be calculated as:

$$T_n = \frac{2A_o f_{y,l} \tan\theta (A_s' + A_s) jd}{2A_o \omega \tan\theta + p_h jd} \tag{9}$$

Table 3.3 Strength of Beams for series 1

Beam Model	Mu.Capacity		Tu.Capacity				Tu Capacity under combined loading	
	Mcr	Mu	Tcr	Tul	Tust	TU Concrete Crushing	Λ	Tn
A1	5.02	5.6	4.03	4.26	7.77	6.32	1	2.61
A2	5.02	5.6	4.03	4.26	7.77	6.32	2	2.11
A3	5.02	5.6	4.03	4.26	7.77	6.32	3	1.77
B1	5.02	11	4.03	5.21	7.77	6.32	1	3.91
B2	5.02	11	4.03	5.21	7.77	6.32	2	3.17
B3	5.02	11	4.03	5.21	7.77	6.32	3	2.66
C1	5.02	11	4.03	6.82	7.77	6.32	1	5.22
C2	5.02	11	4.03	6.82	7.77	6.32	2	4.22
C3	5.02	11	4.03	6.82	7.77	6.32	3	3.55

Strength of Beams in Bending Moment in KN-M (col-3), Torsional Moment in KN-M (Col-5) and Strength of Beams under combined Loading in KN-M (col-9) for series 1 based on 3.3.5 ACI 318-19 design provisions

Table 3.4 Strength of Beams for series 2

Beam Model	Mu.Capacity		Tu.Capacity				Tu Capacity under combined loading	
	Mcr	Mu	Tcr	Tul	Tust	TU Concrete Crushing	Λ	Tn
D1	5.02	8.32	4.03	6.82	4.12	6.32	1	3.91
D2	5.02	8.32	4.03	6.82	4.12	6.32	2	3.17
D3	5.02	8.32	4.03	6.82	4.12	6.32	3	2.66
E1	5.02	8.32	4.03	6.82	5.55	6.32	1	3.91
E2	5.02	8.32	4.03	6.82	5.55	6.32	2	3.17
E3	5.02	8.32	4.03	6.82	5.55	6.32	3	2.66

Strength of Beams in Bending Moment in KN-M (col-3), Torsional Moment in KN-M (Col-6) and Strength of Beams under combined Loading in KN-M (col-9) for series 2 based on 3.3.5 ACI 318-19 design provisions

3.3.6 Geometry of beam Model

In order to have the required λ to achieve the objective of the study the following beam geometry and loading condition are selected.

Table 3.5 Geometry of beam Model

Torsion to Flexure ratio(λ)	Eccentricity (mm)	Length of the overhang (m)
1	300	250
2	600	550
3	900	850

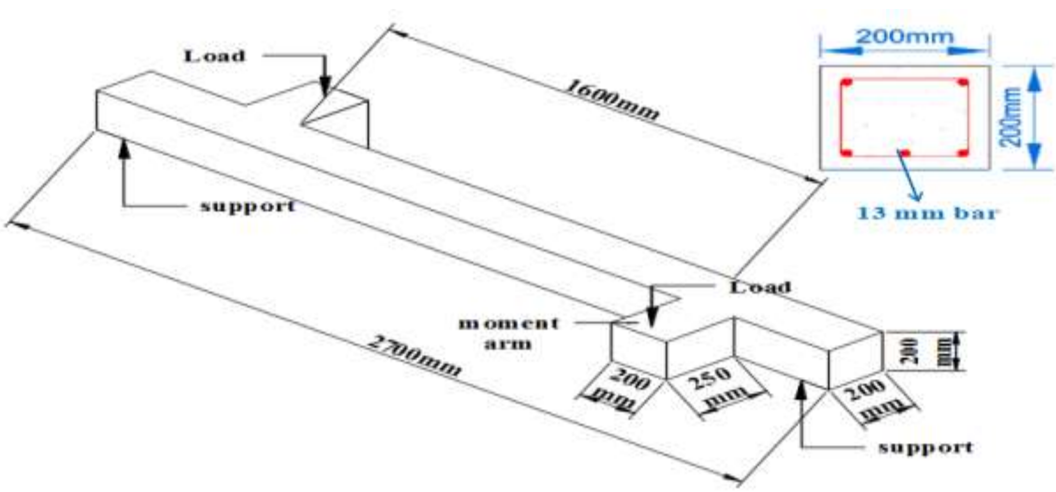

Figure 3.1 Beam setup

3.4 Finite Element Modeling of RC beam

Before modeling the validation works which is described in chapter four is done using method described in this chapter. The modeling procedure is described below and illustrated in the figure

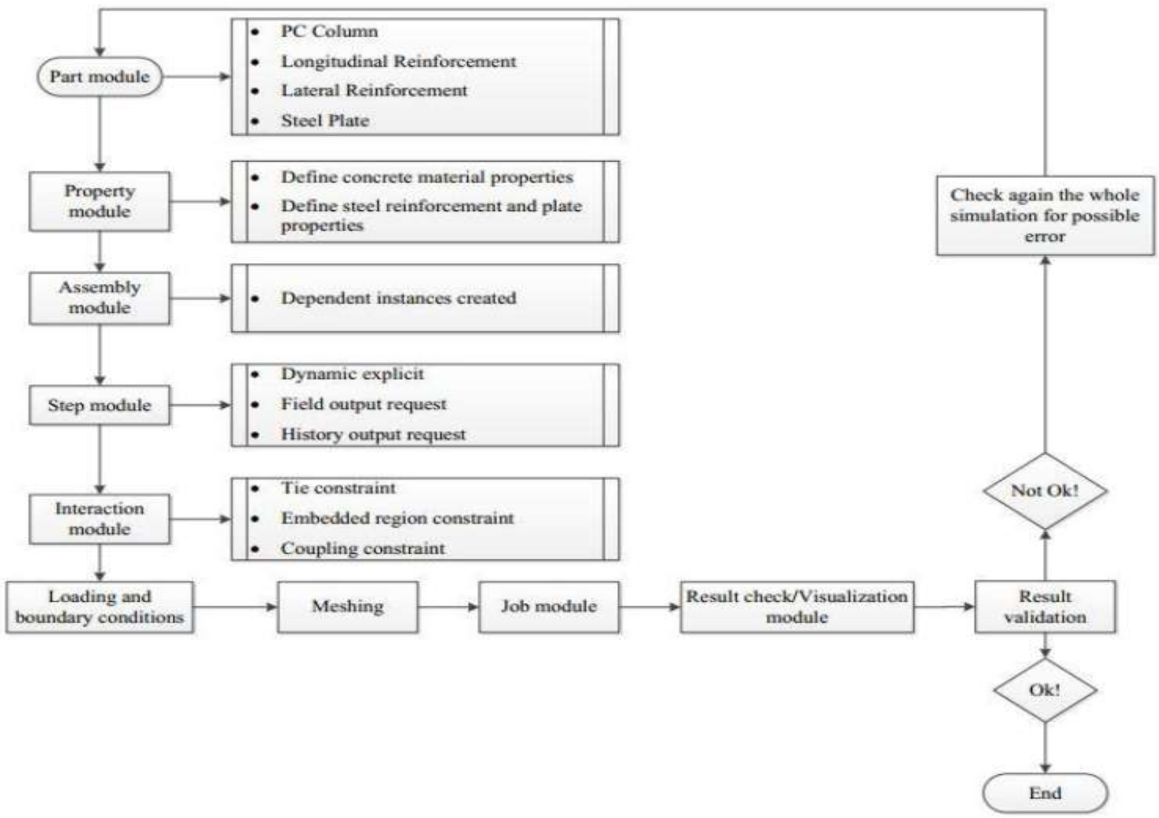

Figure 3.2 Finite Element Modeling

3.5 Geometry, element type and mesh of the model

A three-dimensional numerical model for simulating the Carbon Fiber Reinforced Polymer Strengthened RC Beam Subjected to Bending and Torsion was developed employing the general purpose nonlinear finite element analysis package ABAQUS.

SOLID 65 is used to model the concrete which is suitable for tension cracking, crushing in compression and plastic deformations. It is a three-dimensional element defined by eight nodes. Each node has three degrees of freedom with a presence of translations in the three nodal directions: x, y, and z for each node. Steel reinforcement is modeled using link 180, which is a uniaxial tension-compression element. It includes two nodes, and each node has three degrees of freedom. This element can predict large deflection, large strain, rotation, creep, and plasticity. SOLID 45 is used to model the loading and supporting steel plates. This element is suitable to model the dimensional solid structures defined by eight nodes. There is a presence of translations in the three nodal directions: x, y, and z for each node. This element can predict large deflection, large strain, stress stiffening, creep, and plasticity. For CFRP, the SHELL 181 element type, having four nodes is used in modeling. It is chosen because it is appropriate to analyze thin layered applications. Three translations and three rotations are considered to include the six degrees of freedom at each node.

The geometry of model, along with the reinforcement and meshing of the CFRP sheet for fully U wraps are shown in Figure below.

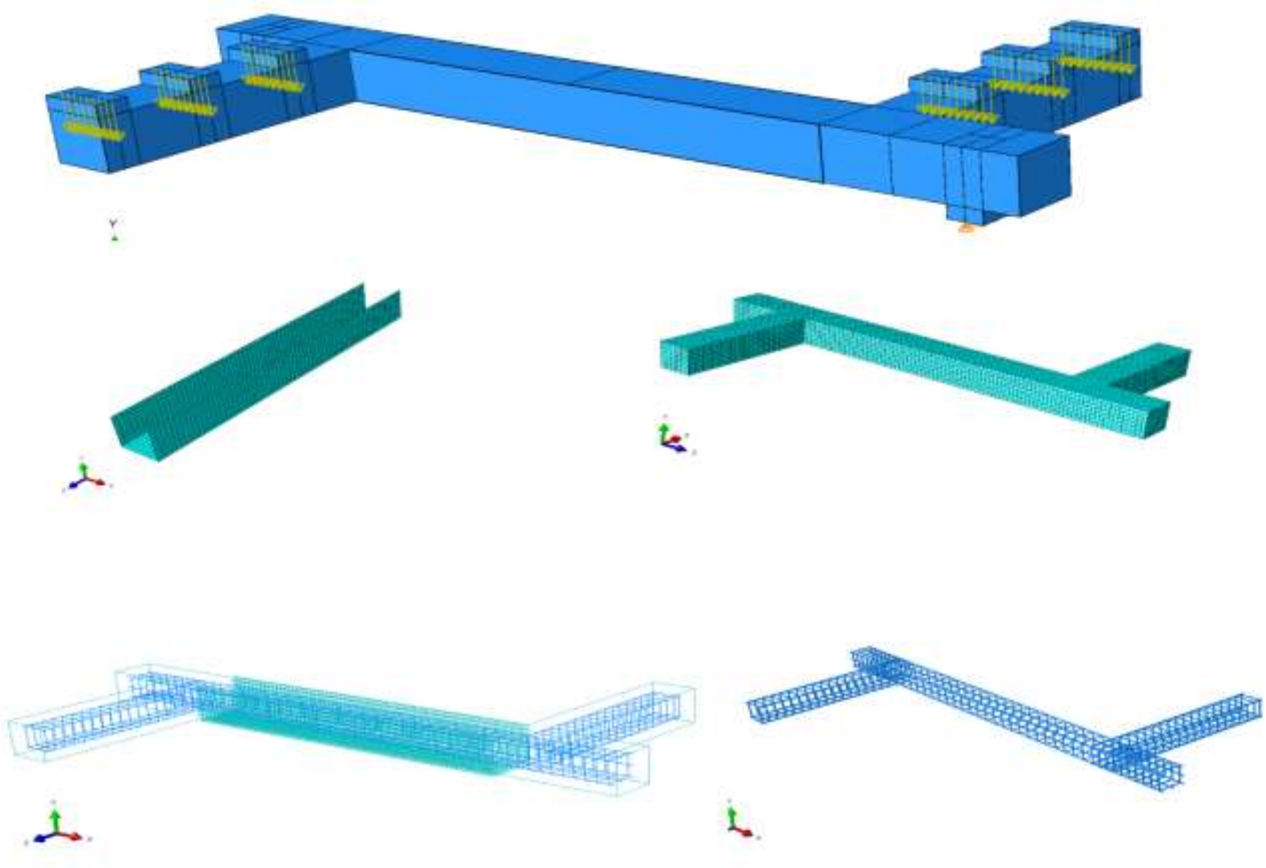

Figure 3.3 Mesh, Loading and Boundary condition

The concrete beam and steel plates were modeled as solid elements while steel reinforcement was modeled as link elements. In the case of strengthened RC beams, the CFRP sheets were modeled as shell element with a mesh size of 25 mm. To ensure the perfect bond between concrete and reinforcement, the link element of steel is connected between each adjacent Solid 65 elements, hence the same nodes are shared between the two materials. The same approach is used for the CFRP sheets to provide the perfect bonding as well as for the Steel plates

3.6 Concrete modeling in ABAQUS

There are three different constitutive models for the analysis of concrete provided in ABAQUS: Each model is designed to provide a general capability for modeling structural steel and reinforcing steel.

The smeared crack model: -is intended for application in which the concrete is subjected to essentially monotonic straining and a material point exhibits either tensile cracking or compressive crushing. Plastic strain in compression is controlled by a compression on yield surface. Cracking is assumed to be the most important aspect of the behavior and the representation of cracking and post cracking an isotropic behavior dominates the modeling.

The brittle cracking model: -is intended for application in which the concrete behavior is dominated by tensile cracking and compressive failure is not important. The model includes consideration of the anisotropy induced by craking.in compression; the model assumes elastic behavior. A simple brittle failure criterion is available to allow the removal of elements from a mesh.

The concrete damaged plastic model: -is based on the assumption of scalar (isotropic) damage and is designed for application in which the concrete subjected to arbitrary loading conditions, such as individual load, cyclic loading, and dynamic loading and so on. The model takes into consideration the degradation of the elastic stiffness induced by plastic straining both in tension and compression. The concrete damaged plasticity model has been used for the concrete in the study.

The CDP model needs a complete stress-strain curve of concrete under compression to define the compressive behavior. The stress-strain curve of concrete under compression to define beyond the ultimate stress into the strain softening region. Two parameters are required to be defined in the tabular format, namely compressive stress σ_c (i.e yield stress) and inelastic strain ε_c^{in}, inelastic strain is total strain minus elastic strain.

$$\varepsilon_c^{in} = \varepsilon_c - \varepsilon_{oc}^{el} \quad \text{.......3.61}$$

Where $\varepsilon_{oc}^{el} = \frac{\sigma_c}{E_o}$ 3.62

E_o=is young modulus of concrete

Once hardening data are given in terms of inelastic strain instead of plastic strain, ABAQUS automatically converts the inelastic strain into plastic strain using the relationship below.

$$\varepsilon_c^{-pl} = \varepsilon_c^{-in} - (\frac{d_c}{1-d_c}) * \frac{\sigma_c}{E_o} \quad \text{.......3.63}$$

In the absence of compressive damage (dc) $\varepsilon_c^{-pl} = \varepsilon_c^{-in}$ the slope is constant E_o and the behavior is assumed to be linear, thus by assuming the tensile ultimate stress to be equal 5-10% of the ultimate unconfined uniaxial.

The stress-strain relations are governed by scalar damaged elasticity:

$$\sigma = (1-d) D_o^{el} * \varepsilon_c - \varepsilon_{oc}^{el} = D^{el} * (\varepsilon_c - \varepsilon_{oc}^{el}) \quad \text{.......3.64}$$

$$D^{el} = (1-d) * D_o^{el} \quad \text{.......3.65}$$

Where D_o^{el} is the initial (undamaged) elastic stiffness of the material D^{el}=(1-d) D_o^{el} is the degraded elastic stiffness; and d is the scalar stiffness degradation variable, which can take values in the range from zero (undamaged variable) to one (fully damaged material) and known as dc for concrete under compression. Damage associated with the failure mechanisms of the concrete (cracking and crushing) therefore result in the elastic stiffness. For this paper scalar damaged or stiffness degradation of compression is accounted. ABAQUS uses the elastic definition to determine the material response until the material reaches the defined cracking stress, after which the non-linear behavior of the materials governs. These material properties are defined using the elastic command within the ABAQUS software package. To properly define the CDP, many different commands need to be utilized. ABAQUS uses the elastic definition to determine the material response until the material reaches the defined cracking stress, after which the non-linear behavior of the materials governs. These material properties are defined using the elastic command within the ABAQUS software package.

Table 3.6 Concrete damage Plasticity Parameter

Dilation angle	31
Flow potential eccentricity e	0.1
Ratio equibiaxial compressive yield stress to initial uniaxial compressive yield stress	1.16
Ratio of the second stress invariant on the tensile meridian.Kc	0.6
Viscosity Parameter	0

Table 3.7 Material properties of Concrete

Density	2.4E-09	(kg/m^3)
fck=	36.54	Mpa
Eci=	28410	Mpa
v=	0.17	
ftm=	3.75	Mpa
ftr=	10.67	Mpa
ε1=	0.0004	
εo=	0.0026	

Damage associated with the failure mechanisms of the concrete (cracking and crushing) therefore result in the elastic stiffness. For this paper scalar damaged or stiffness degradation of compression is accounted. ABAQUS uses the elastic definition to determine the material response until the material reaches the defined cracking stress, after which the non-linear behavior of the materials governs. These material properties are defined using the elastic command within the ABAQUS software package. To properly define the CDP, many different commands need to be utilized. Damage associated with the failure mechanisms of the concrete (cracking and crushing) therefore result in the elastic stiffness. For this paper scalar damaged or stiffness degradation of compression is accounted. ABAQUS uses the elastic definition to determine the material response until the material reaches the defined cracking stress, after which the non-linear behavior of the materials governs. These material properties are defined using the elastic command within the ABAQUS software package. To properly define the CDP, many different commands need to be utilized.

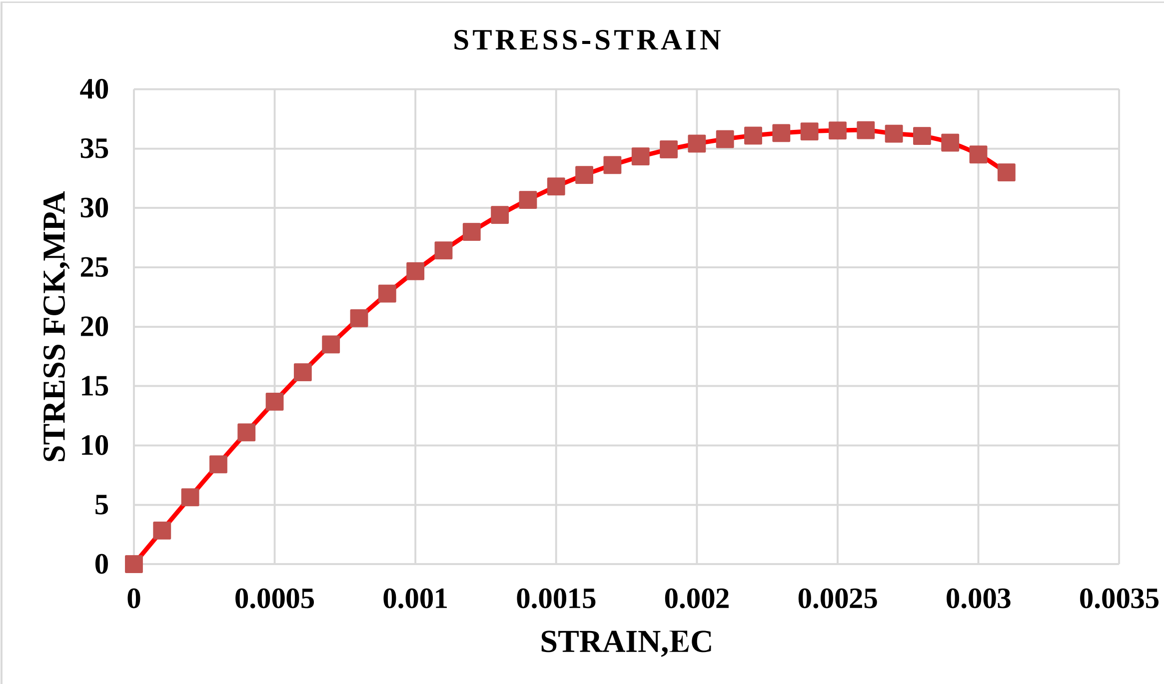

Figure 3.4 Compressive stress-strain diagram of concert

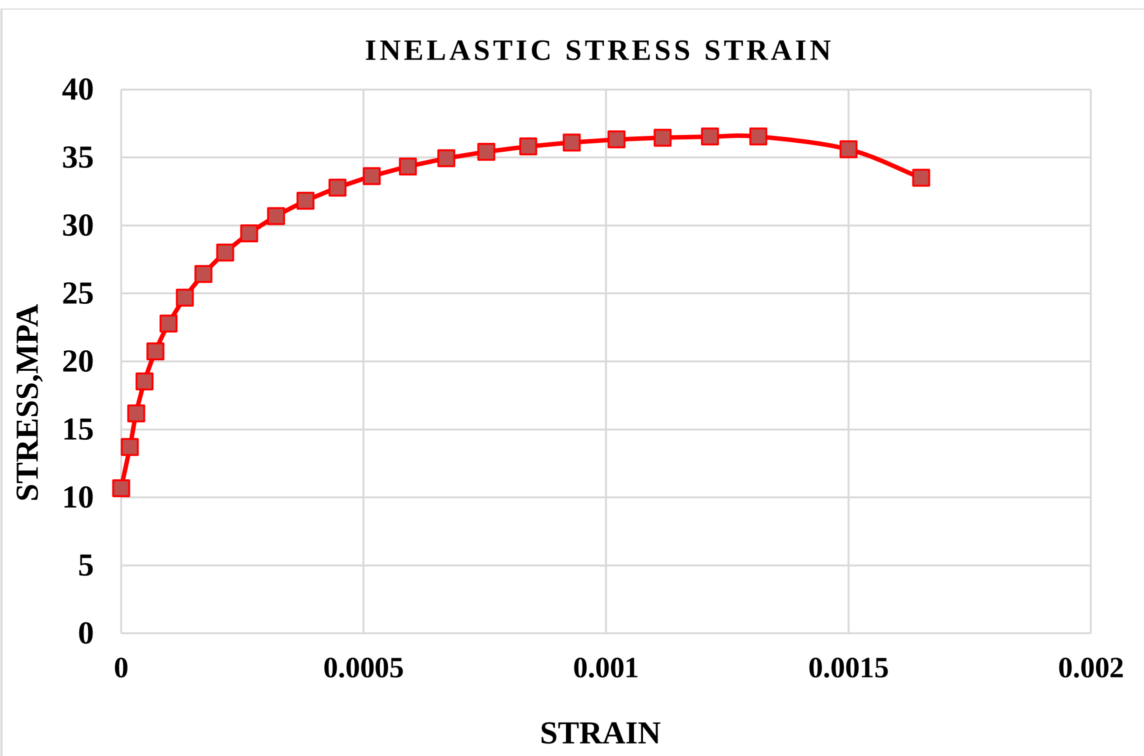

Figure 3.5 Compressive stress-crushing strain diagram of concrete.

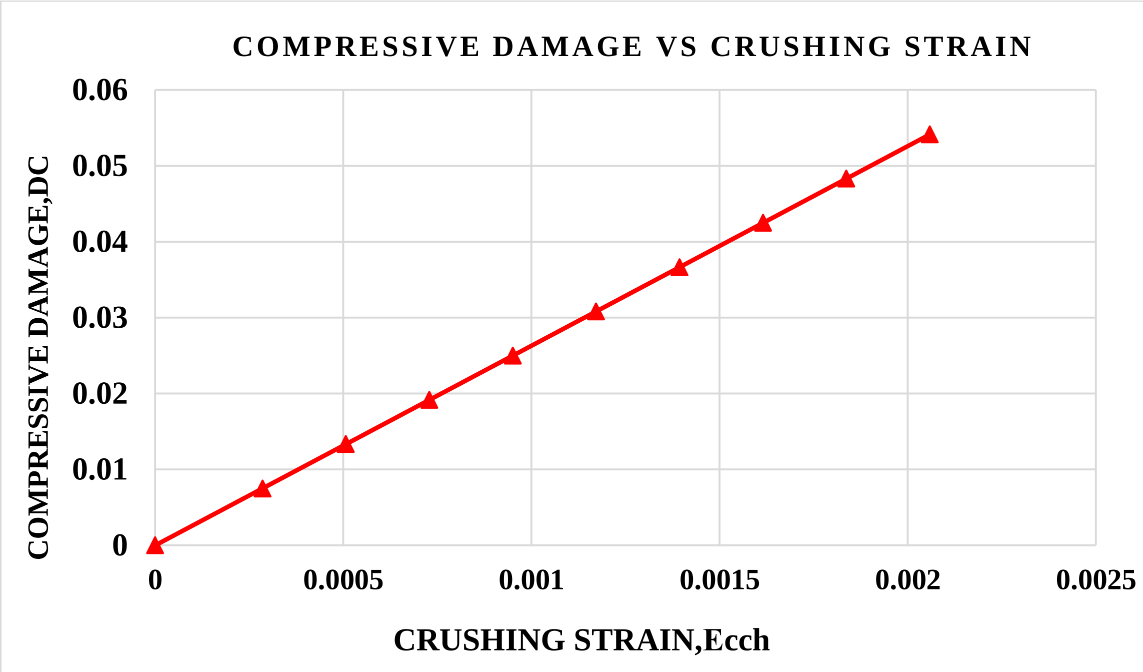

Figure 3.6 Compressive damage-crushing strain diagram of concrete.

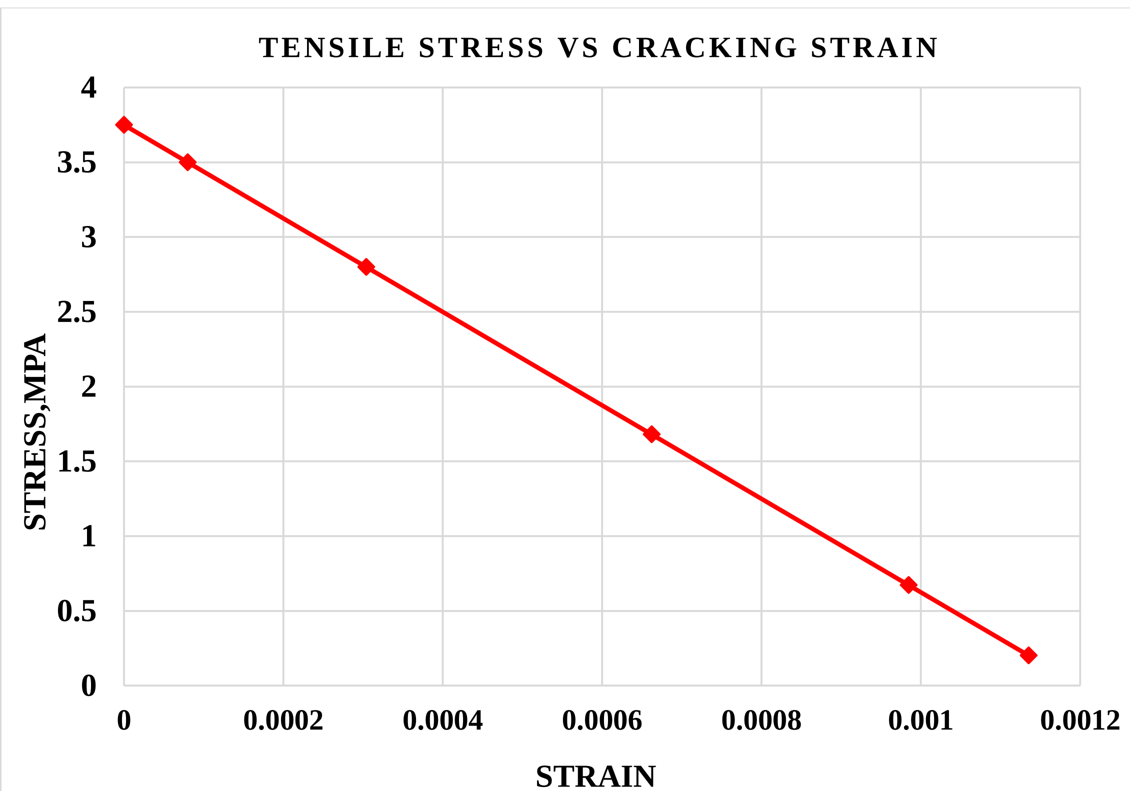

Figure 3.7 Tensile stress-cracking strain diagram of concrete

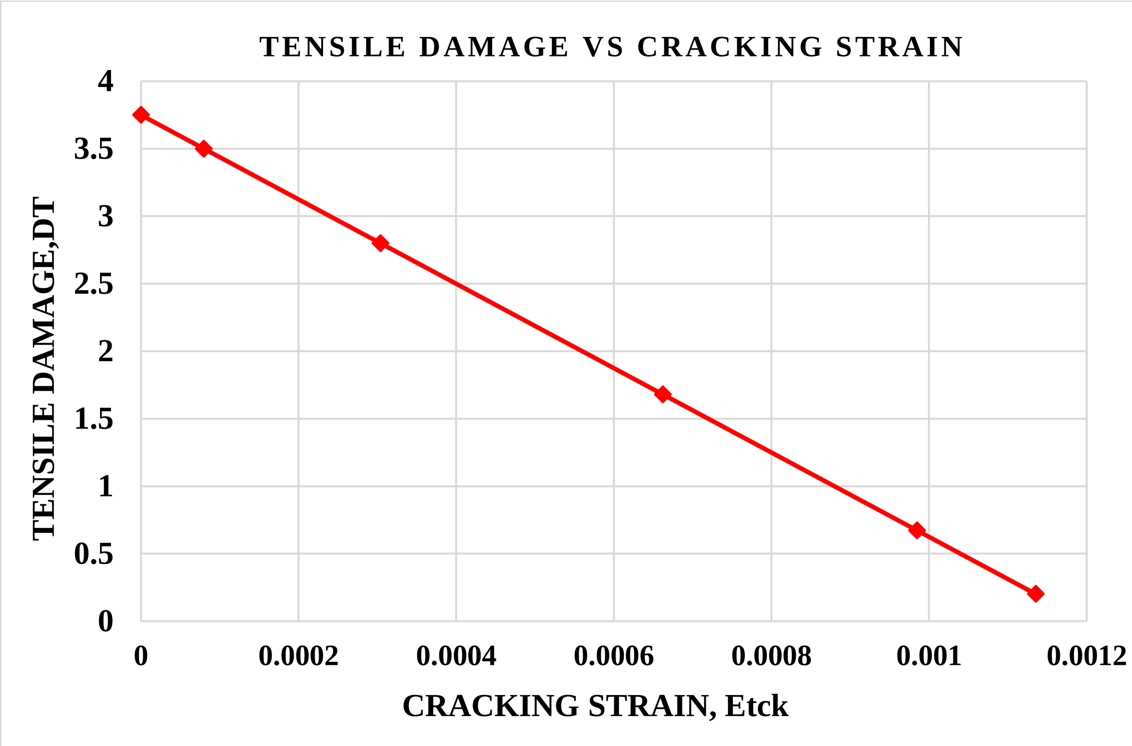

Figure 3.8 Tensile damage variables-cracking strain diagram of concrete

3.7 CFRP modeling in ABAQUS

3.7.1 FE representation of laminates and laminate structures

Laminates and laminate structures commonly have geometries with small thicknesses compared to their lateral expansion. Accordingly, there is the legitimate desire to represent the three-dimensional continuum by a condensed two-dimensional structural model. The governing equations and the associated boundary conditions of the reduced model are than derived upon an elimination of the thickness coordinate by integrating along the thickness the partial differential equations of the three-dimensional continuum .A large number of theories and associated finite element definitions have been created over the years to achieve the compliance with the basic requirements for the stress, strain and displacement fields over a laminate's through-thickness direction. There are two approaches to represent laminate structures in Abacus software.

Equivalent single layer approaches

The family of Equivalent single layer (ESL) models comprises those models which are to be regarded as direct extensions of approaches established for homogeneous structures to multilayered structures. Without taking explicitly into account the characteristics induced by bi-material interfaces these models commonly introduce through-thickness assumptions for the displacement field.

Layer-wise approach

Assuming a separate displacement field for each layer – i.e. layer-wise (LW) – is a straight forward approach to explicitly account for the heterogeneous cross-section of a laminate. On the laminate level, the expressions of the layer-wise assumptions are assembled without enforcing a continuous through-thickness strain field.

3.7.2 Material definitions for laminates

Although it has been stated that the availability of advanced multi-layered plate theories is limited in commercial FE codes, the described fundamental difference between equivalent single layer (ESL) and layer-wise (LW) approach is also reflected in the way in which the laminate behavior is provided to a commercial FEA. Whereas the ESL approach condenses the inhomogeneity of the material in through-thickness direction in just one material description, the LW approach preserves

Equivalent single layer method

Using this approach, the laminate stacking sequence is interpreted as part of the material description and consequently entered in the material definition part of the FEA. The commercial code ABAQUS offers convenient graphical user interfaces to create and monitor the stacking sequence information consisting of the material definition of each individual lamina. The necessary through-thickness integration is controlled by the number of z-integration point at which the requested results (commonly stresses and strains) are output, too. Assigned to the suitable shell or continuum shell elements the created laminate section represents the whole stacking sequence in just that element. This means that the single-layer equivalent approach requires exactly one element for the discretization of the contained laminate stacking sequence in z-direction. If the resolution in z-direction shall be refined it is possible to increase the number of z-integration points. Alternatively, the stacking sequence is in parts condensed in several ESL sections which have to be assigned to the adequate number of elements stacked in thickness direction.

Layer-wise method

The layer-wise method to provide the laminate behavior is a combination of the separate orthotropic material definitions of each lamina and the geometric representation of the laminate stacking sequence. Hence the effort to describe the laminate behavior has been transferred from the material definition to the geometrical representation of the laminate. Accordingly the number of elements in thickness direction depends on the number of laminae incorporated in the respective laminate whereas a minimum discretization by one element per layer is required. The resolution in z-direction is defined by the number of elements per layer stacked in through-thickness direction. Generally, the LW method results in a greater number of elements associated with a greater computational effort, but the suitable continuum shell and continuum elements provide more accurate results.

3.7.3 Element types for laminate structures

FEA provides a wide variety of elements not only for 3D stress analysis in laminates and laminate structures but also for the analysis of thermal residual stresses and delamination In the following the capabilities and applicability of typical commercial element types for the laminate representation are summarized using with small thicknesses compared to their lateral extension it may be reasonable to reduce the geometry to its mean surface, thus to a flat, locally 2D geometry without a geometrical extension in through-thickness direction. In this case the local thickness of the structure is interpreted as a material parameter. Alternatively, the local thickness of the structure may be retained in the discretized geometry which results in a fully three-dimensional FE representation of the structure. This decision regarding the geometric representation of the structure influences the choice of element types described below and thus the suitable material definition method

Shell elements

the most conventional group of element types associated with the representation of geometries with small thicknesses compared to their lateral extension are shell elements.

Continuum shell elements

Continuum shell element are generally based on the kinematics and equations of work defined for conventional shell elements. However, they are used to discretize fully 3D geometries. They automatically derive the shell thickness information from geometry if the shell normal has been correctly defined by the user. The necessary shell-analog strain measures are related to the exclusively available translator degrees of freedom at the eight corner nodes. Continuum shell elements generally provide the same output.

Solid continuum elements

Solid continuum elements are not commonly recommended for the discretization of geometries with small thicknesses compared to their lateral extension because the accuracy of these groups of elements relies on balanced spatial proportions. In the case of laminate structures this requirement eventually results in a lateral discretization density which equals at least the lamina thickness. If possible, at all, this is extremely computationally expensive.

3.7.4 Classification and Overview of Failure Criteria for composites

In damage analysis there are in general two different types of failure criteria for CFRP material, namely

- for damage initiation: Strength of Material Criteria based on stresses and
- for damage growth: Fracture Mechanics Criteria based on energy

Strength of Material Criteria

Strength of material criteria is used to calculate the initiation and onset of propagation in static analysis based on stresses. Literature offers a large number of stress-based failure criteria.

Among many failure criteria relevant to isotropic materials are the maximum normal stress Rankine), maximum shear stress (Tresca), maximum normal strain (Saint–Venant) and maximum strain theory (Von Mises)

For metals it is common to calculate one equivalent stress (e.g., von Mises, or Tresca) to predict damage initiation. However, in composite materials the damage mechanisms are multiple, having different underlying micromechanical reasons .Currently, there are several failure criteria for composites. Strength of material criteria is used to calculate the initiation and onset of propagation in static analysis based on stresses. Literature offers a large number of stress-based failure criteria. Simple methods early invented but still recognized were developed by Hill [40], Tsai et al [41] and Hashin [42]

Hill [40] based on the von Mises criterion, established one of the first failure criteria for anisotropic materials, which is a generalization of the flow behavior for isotropic materials. Although it is a more general criterion, it has as a drawback: the determination of several parameters to establish the complete equation of the model. In 1965, Tsai proposed a modified Hill criterion where he quantified the traction and compression inequality for orthotropic materials, which was called the Tsai–Hill criterion [40,41]. For several authors, the Tsai–Hill criterion is one of the best and most widely Polymers 2020, 12, 818 15 of 59 used failure criteria for laminates because it considers the interactions between the stress components; however, this criterion is not invariant in relation to the coordinate system; therefore, only orthotropic materials should be applied .Despite being considered one of the best failure criteria, many consider that this criterion has several deficiencies in its theoretical basis [40,41] cites that there are basically three deficiencies in Tsai–Hill's theory; namely:

- It does not intrinsically consider differences in tensile and compressive strength.
- It does not present good results in the state of loading by compression in the three main axes.
- It supposes that a hydrostatic state of stresses cannot cause failure—in the case of anisotropic materials, a hydrostatic state of stress causes shear deformation and failure.

Tsai et al [41] presented a criterion based on the Tsai–Hill criterion, aiming to increase the number of terms in the Tsai–Hill failure criterion equation, to better approximate the experimental data, considering a two-dimensional stress state .The Tsai–Wu criterion is an interactive criterion, which provides for component rupture due to the combination of tensions acting on the part. In addition, this criterion, in its three-dimensional form, takes into account the effect of the hydrostatic component of the stresses differently from the previously described criteria.

The interactions between the stress components are independent of the material properties. However, since it is not a failure criterion based on physical phenomena, it can predict the occurrence of the damage, but cannot distinguish between the different failure modes; it can only predict whether or not the failure occurs in the structure. The Tsai–Wu criterion became one of the most used criteria, and to this day several works are developed based on the same. Hashin, in 1980, proposed a failure criterion divided into sub criteria, for failure in unidirectional fiber reinforced sheets—transversely isotropic—based on the quadratic polynomial of tensions Differently from the Tsai–Hill and Tsai–Wu criteria, which do not allow an identification of failure modes; the Hashin criterion considers modes of failure of the fiber and matrix, distinguishing between tensile and compression loads, addressing four main modes: traction and compression of the fibers and matrix According to Laurin, Carrere and Maire the historical importance of this criterion is that it started a different way of designing failure criteria for composite materials. Hashin [40] first identified the predominant failure modes, and subsequently the variables associated with these modes, and then proposed the interactions between the variables involved in each failure mode. Despite the wide use of failure criteria, they present many difficulties regarding the accuracy of the results, because of undesired failure modes; plastic deformations and geometric nonlinearity of the parts; the effect of the residual tensions of the composite fabrication; and dispersions in the experimental results due to the heterogeneous nature of the materials. Many software developers have implemented multiple failure criteria and therefore let the user decide, which is appropriate for a certain application. For example, Abaqus has implemented Hashin's failure criteria.

Because of the complexity related with failure of composite materials four equations are defined within Hashin's theory in order to consider four different damage mechanisms. The equations are defined as the following

Hashin based damage initiation criteria:

Fiber tension$(\sigma_{11} \geq 0)$:

$$F_f^t = \left(\frac{\sigma_{11}}{X^T}\right)^2 + \alpha\left(\frac{\tau_{12}}{S^L}\right)^2 \geq 1 \tag{4.2}$$

Fiber compression$(\sigma_{11} < 0)$:

$$F_f^c = \left(\frac{\sigma_{11}}{X^C}\right)^2 \geq 1 \tag{4.3}$$

Matrix tension$(\sigma_{22} \geq 0)$:

$$F_m^t = \left(\frac{\sigma_{22}}{Y^T}\right)^2 + \left(\frac{\tau_{12}}{S^L}\right)^2 \geq 1 \tag{4.4}$$

Matrix compression$(\sigma_{22} < 0)$:

$$F_m^c = \left(\frac{\sigma_{22}}{2S^T}\right)^2 + \left[\left(\frac{Y^C}{2S^T}\right)^2 - 1\right]\frac{\sigma_{22}}{Y^C} + \left(\frac{\tau_{12}}{S^L}\right)^2 \geq 1 \tag{4.5}$$

where XT is the longitudinal tensile strength, XC the longitudinal compressive strength, $Y\,T$ the transverse tensile strength, $Y\,C$ the transverse compressive strength, SL the longitudinal shear strength, ST transverse shear strength, $\sigma 11;\ \sigma 22;\ \tau 12$ are the components of the stress tensor $\boldsymbol{\sigma}$ and α is the coupling parameter between $\sigma 11$ and $\tau 12$

Material input Properties for CFRP

Sika Wrap Hex 300C 0/90 is the CFRP type used in this study. It is a bi-directional material property with 0.166 mm thickness and having fibers in longitudinal and transverse directions. The linear elastic tensile stress-strain curve for CFRP composites is shown in Figure 3.9 and the detailed mechanical properties and poison's ratio in all directions, are shown in table 3.8

Table 3.8 Material properties of CFRP

Modulus of elasticity (GPa)		Poison's ratio		Shear modulus of elasticity (GPa)		Ultimate tensile strength (MPa)	Ultimate strain
E_x	260	V_{xy}	0.22	G_{xy}	106.6		
E_y	260	V_{yz}	0.22	G_{yz}	106.6	3900	0.015
E_z	4.5	V_{zx}	0.30	G_{zx}	1.73		

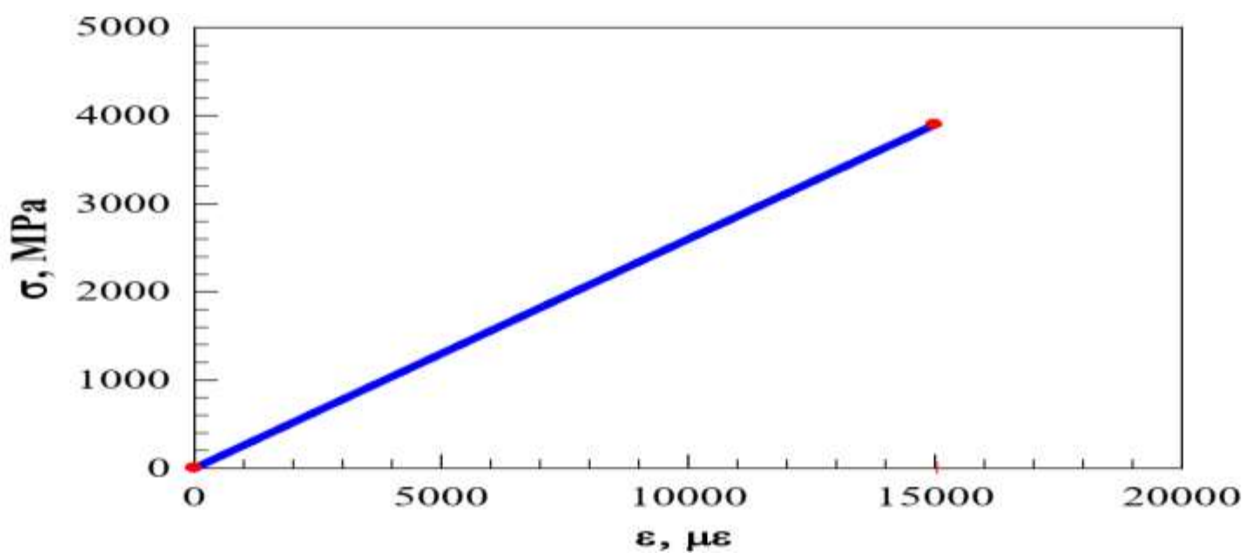

Figure 3.9 Stress vs Strain for CFRP

Table 3.9 Hashin Damage input

Longitudinal Tensile Strength (Mpa)	Longitudinal Compressive Strength (Mpa)	Transversal Tensile Strength (Mpa)	Transversal Compressive Strength (Mpa)	Longitudinal Shear Strength (Mpa)	Transversal Shear Strength (Mpa)
2050	972	62	190	81	81

Table 3.10 Damage Evolution

Longitudinal Tensile fracture energy	Longitudinal Compressive fracture energy	Transversal Tensile fracture energy	Transversal Compressive fracture energy
95	103	0.2	0.2

Table 3.11 Damage Stabilization

Viscosity coefficient in the longitudinal tensile direction	Viscosity coefficient in the longitudinal Compressive direction	Viscosity coefficient in the Transversal Tensile direction	Viscosity coefficient in the Transversal Compressive direction
0.1	0.1	0.1	0.1

3.8 Reinforcing steel and structural steel modeling

Steel is a homogeneous material, and the stress-strain behavior can be assumed to be identical in tension and compression. Steel bar in reinforced concrete member is normally long and relatively slender and therefore, they can be generally assumed to be capable of transmitting axial force only. The reinforcement was assumed to be elastic perfectly plastic.

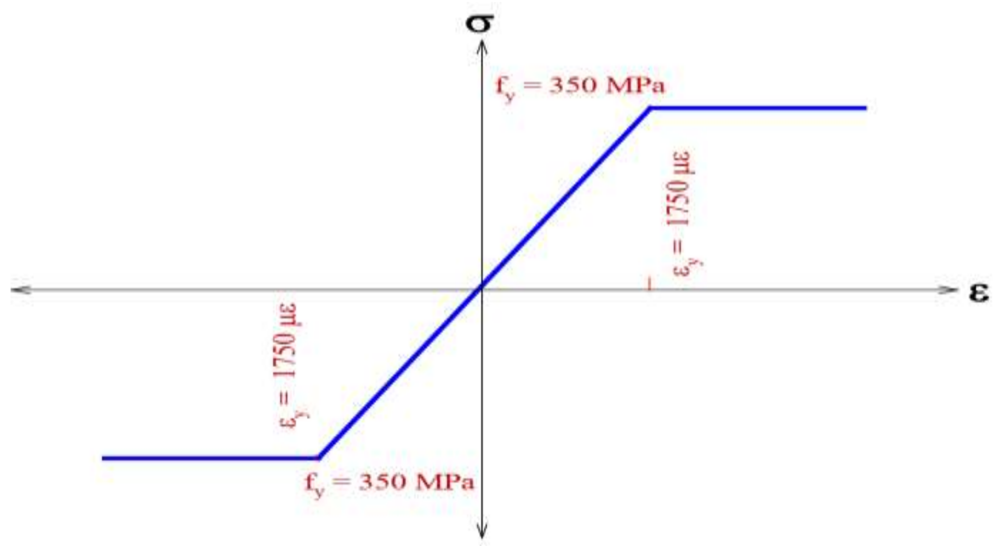

Figure 3.0.10 Stress vs Strain for Steel

Table 3.12 Material properties for steel

Density	7.85E-09	(kg/m^3)
fy=	350	Mpa
Es=	2.00E+05	Mpa
v=	0.3	
εy=	0.00175	

CHAPTER FOUR

RESULT AND DISCUSSION

4.1 Introduction

This chapter presents the results obtained using the finite element analysis method through the use of the program, ABAQUS. The results obtained were discussed with respect to each independent variables

4.2 Validations

To validate the application of the present finite element modeling for further analysis two reference sets of study are used. [31]

Firstly, the moment-strain curve data of the center bar of longitudinal reinforcement obtained from numerical analysis is compared with moment-strain curve of an experimental result reported by Gesund et. al. [35].as shown in figure below the moment –strain curves obtained from the numerical study closely follows the experimental curves. However, significant deviations are seen between the experimental and numerical curves between cracking and ultimate stage. The ultimate bending moment obtained from experiment is around 11.52KN-M while the ultimate bending moment obtained from finite element analysis is 12.1KN-M which is around 5% higher.

Secondly, the moment deflection data obtained from NLFEA using ABACUS is compared with the moment deflection curve obtained from NLFEA using ANSYS which is reported by Al-Rousan, et. Al. [35] as shown on figure below. The load deflection curve follows same path however due to concrete material modeling difference there is a slight difference in path. The ultimate deflection obtained from ANSYS is around 4.88mm and the ultimate deflection obtained from ABACUS is around 4.85mm. Generally, there is good agreement for both sets of data used for validation which allows us to use the application of the present finite element modeling for further analysis.

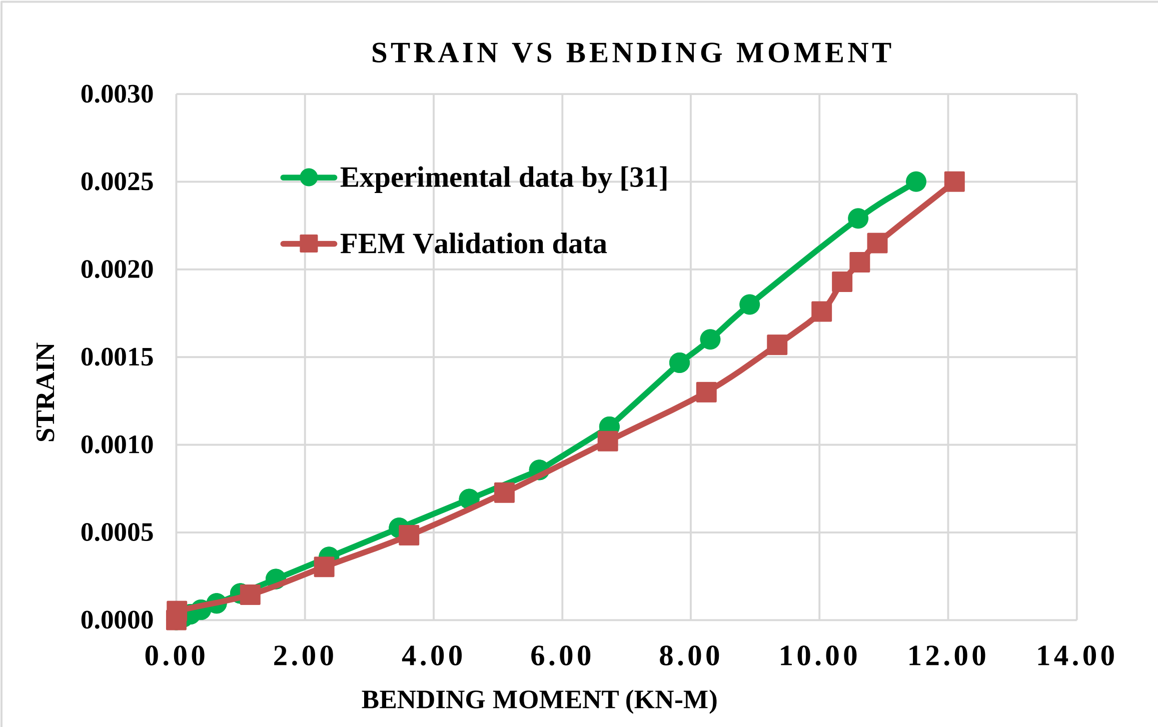

Figure 4.1 Strain in the center bar of Longitudinal tension reinforcement

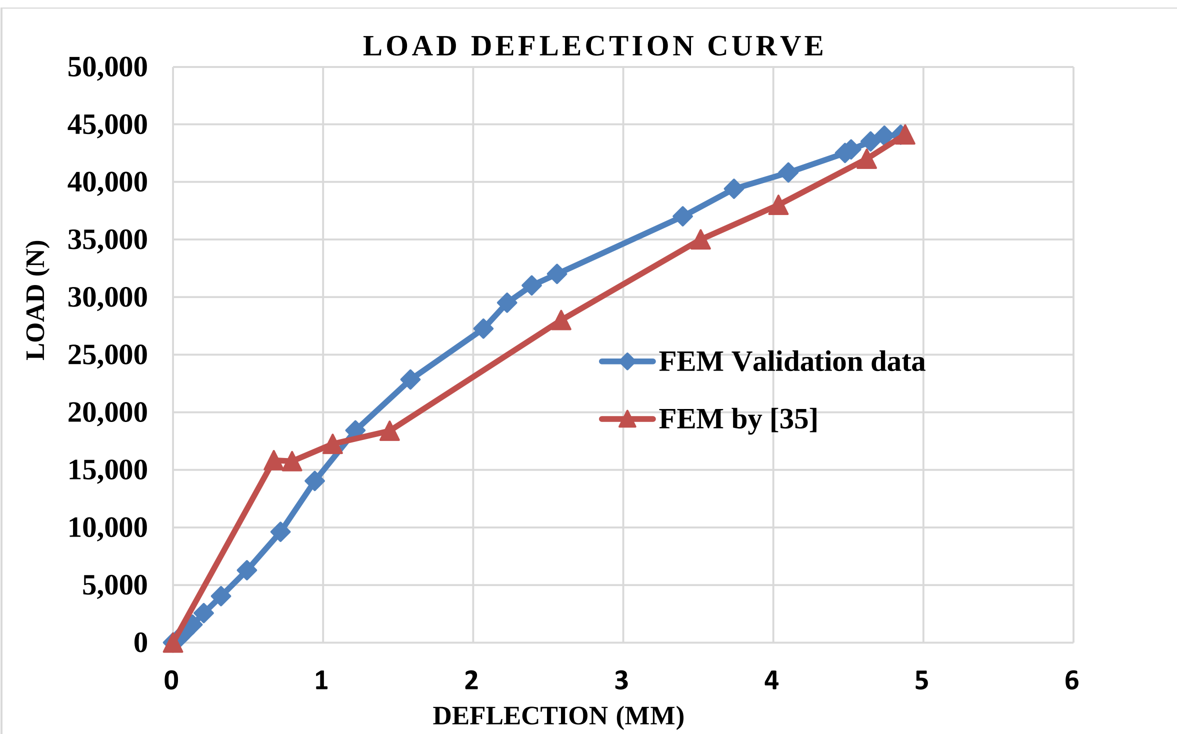

Figure 4.2 Load Deflection Curve

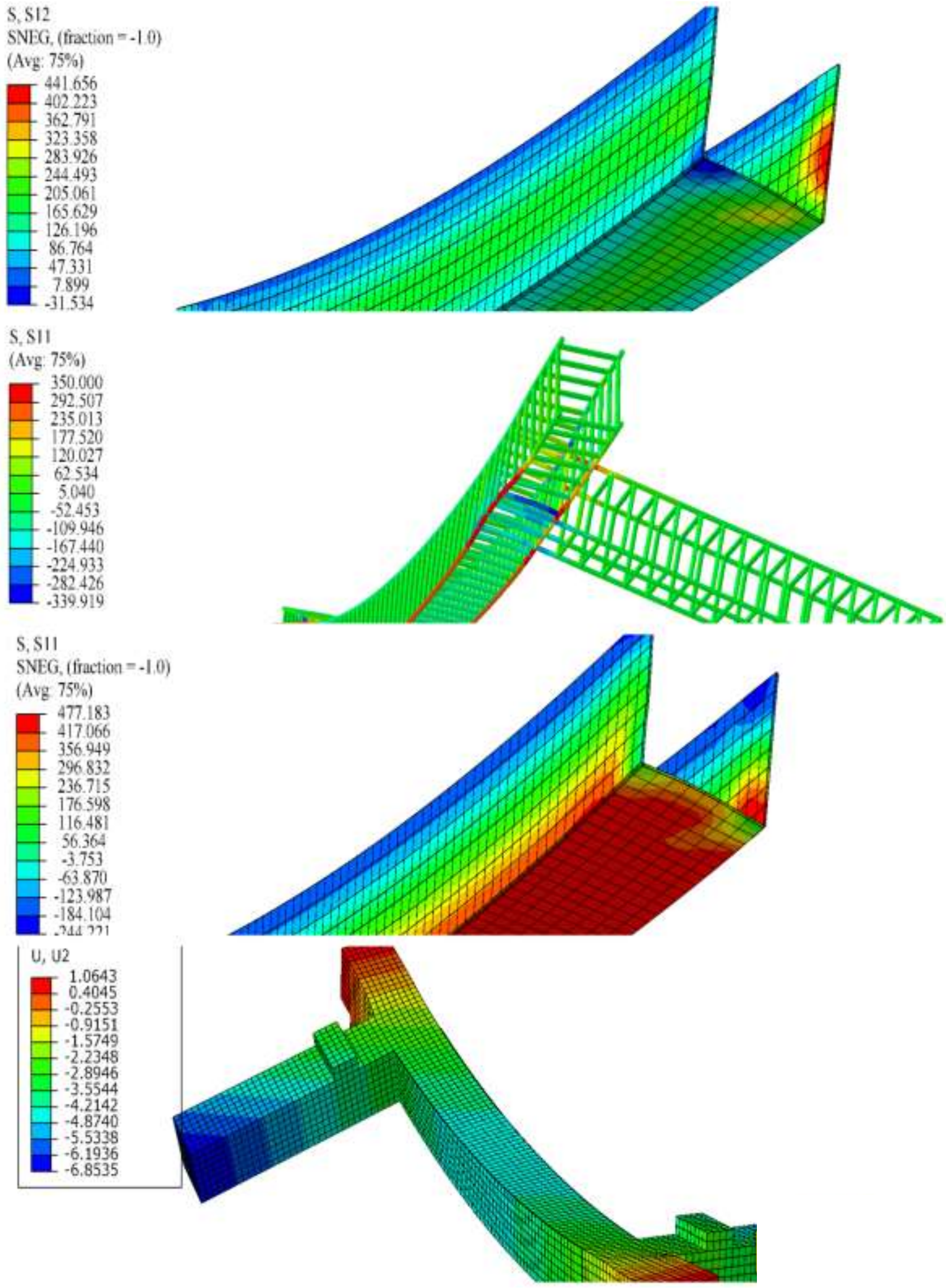

Figure 4.3 Stress and deflection

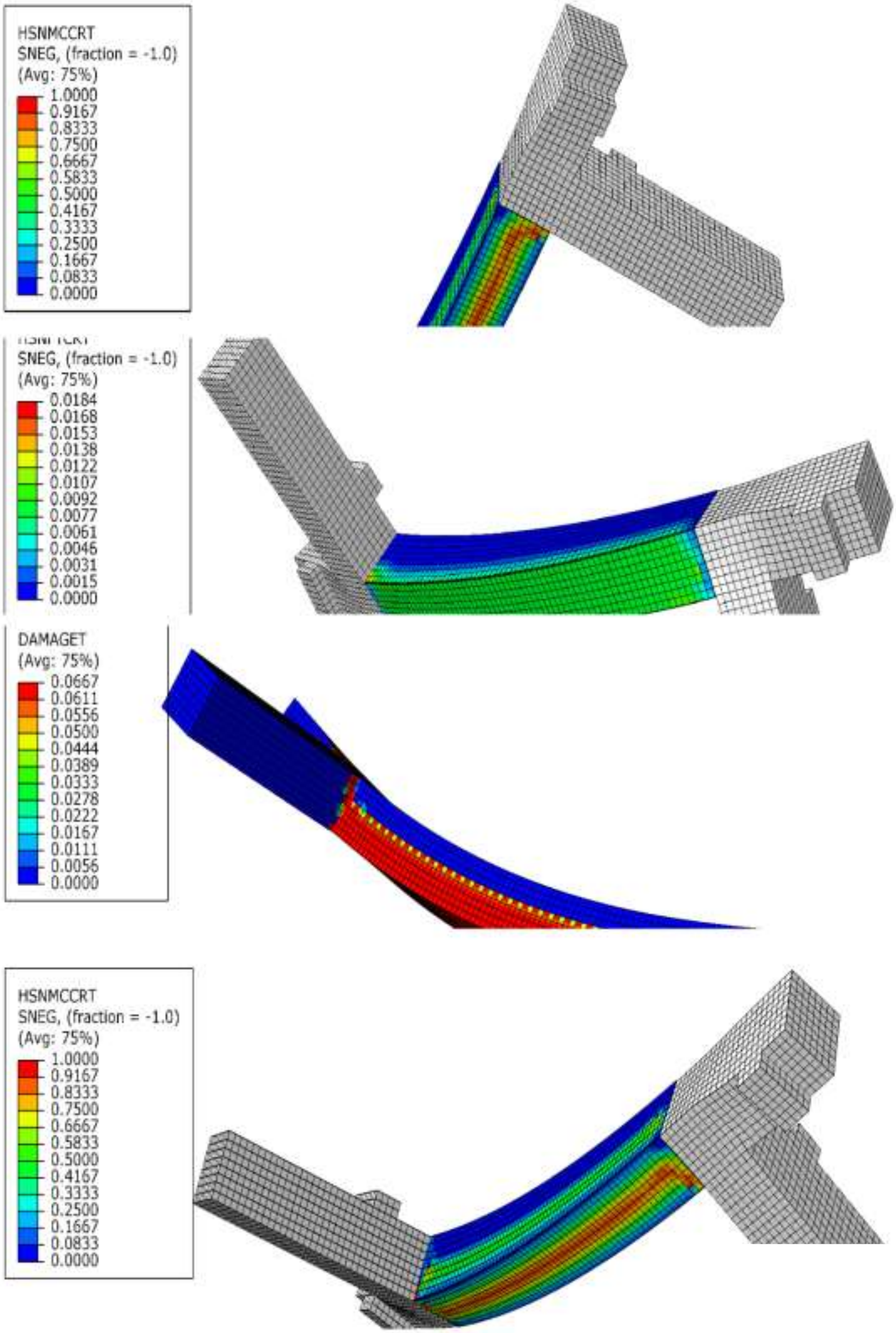

Figure 4.4 Damage parameters for Concrete and CFRP

4.3 Results

The bending moment and torsional strength values are presented for series 1 and series 2. The using this values effect of different variables is studied independently under each series.

Table 4.1 Strength properties of beams for series 1

SN	Beam Category	Mu KN-M	Tu KN-M
1	A1	15.44	15.44
2	A2	8.81	17.62
3	A3	5.81	17.42
4	B1	16.07	16.07
5	B2	9.13	18.25
6	B3	5.74	17.22
7	C1	16.12	16.12
8	C2	9.03	18.06
9	C3	5.81	17.42

Table 4.2 Strength properties of beams for series 2

SN	Beam Category	Mu KN-M	Tu KN-M
1	D1	15.39	15.39
2	D2	9.00	17.99
3	D3	5.70	17.09
4	E1	16.20	16.20
5	E2	9.22	18.45
6	E3	6.21	18.63

Effect of T/M

The numerical results presented in Table 4.1 are reproduced and interpreted. The Figure below shows the relationships between torque and torque-moment ratios (T/M) at the level of ultimate torque. Data of three different samples (Beam-A, Beam-B and Beam-C) with different percentages of longitudinal tensile and compressive reinforcement have been presented. Each of the lines in the figure reflects the nature of a particular beam with the same amount of longitudinal reinforcement but with different values of T/M. It can be observed that the torsional strength increases significantly for torque moment ratios between 1 and 2. For beam A as λ changes from 1 to 2 the ultimate torsional strength increases from 15.44 KN-M to 17.415 KN-M or there is 12.37% improvement in strength. For beam B as λ changes from 1 to 2 the ultimate torsional strength increases from 16.06 KN-M to18.25 KN-M or there is 12% improvement in strength. For beam C as λ changes from 1 to 2 the ultimate torsional strength increases from 16.12 KN-M to18.05 KN-M or there is 10.73% improvement in strength. However, for torque moment ratios between 2and 3 the torsional moment decreases moderately.

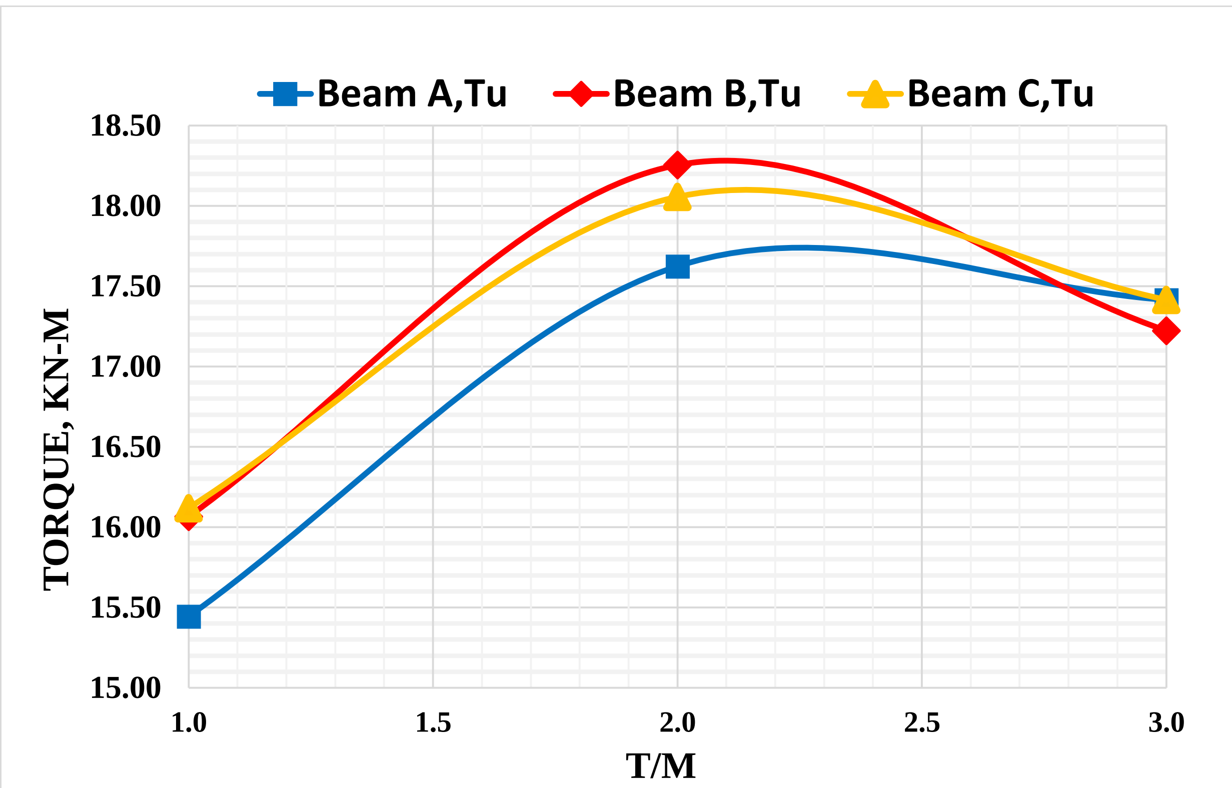

Figure 4.5 Effect of T/M

Effect of Longitudinal Tensile Reinforcement

In order to reflect the effect of longitudinal tensile reinforcements on the torsional strength of sample A and B were compared. The torque moment ratio (T/M) for each of the samples was adopted as 1, 2and 3. Two different percentages of tensile reinforcements 0.2512 and 0.5024 were used keeping the compression reinforcement as a constant value of 0.2512 percent (Refer Table 3.1). Data presented in Figure below show that at ultimate torque effect of longitudinal reinforcement is slightly observed. It has been observed for torque to bending ratio of 1 and 2 that ultimate torque slightly increases. For λ=1 the ultimate torsional strength increases from 15.45 KN-M to16.07 KN-M or there is 4% improvement in strength. For λ=2 the ultimate torsional strength increases from 17.62 KN-M to18.26 KN-M or there is 4% improvement in strength. For λ=3 ultimate torsional strength decreases with the increment of tensile reinforcement.

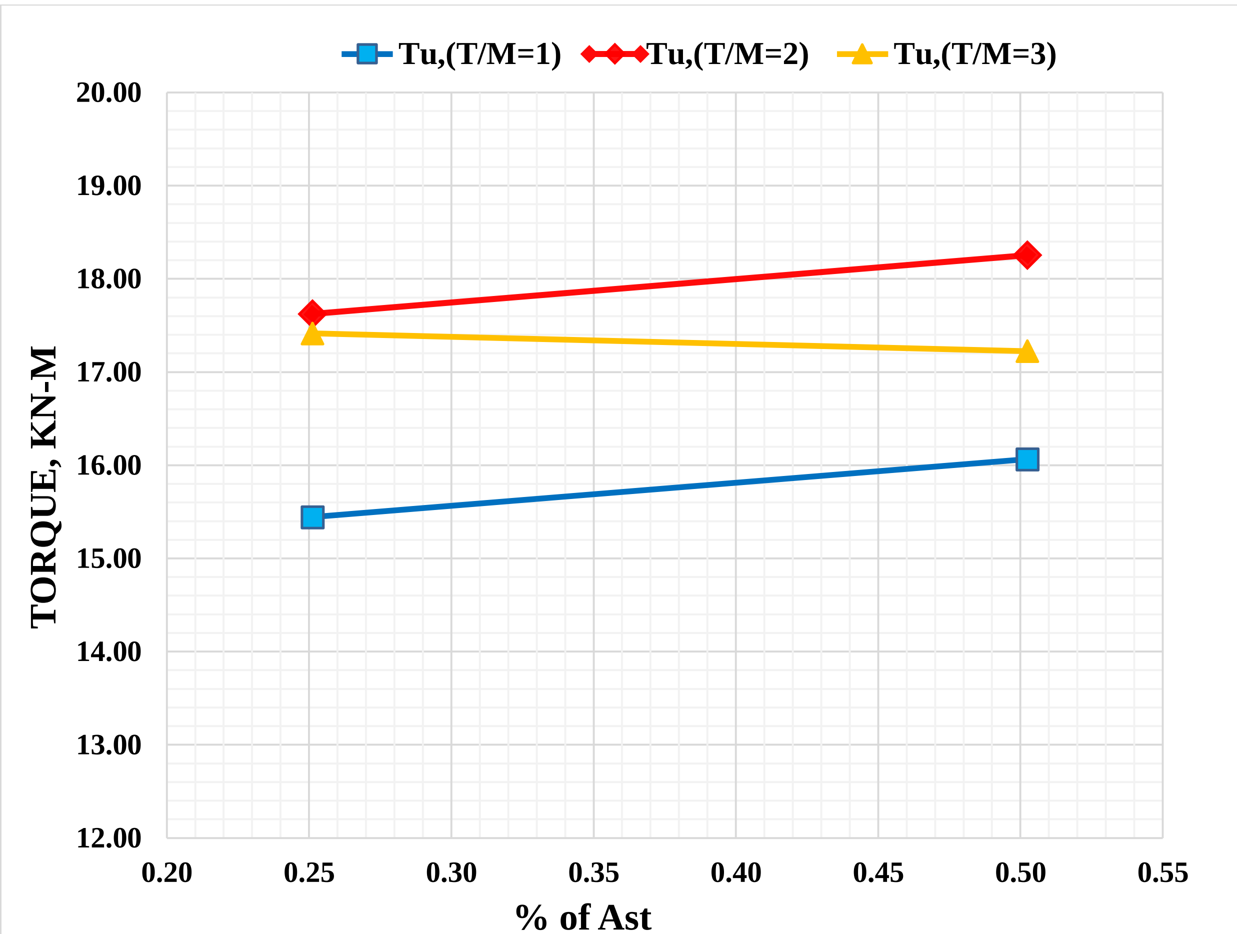

Figure 4.6 Effect of Longitudinal Tensile Reinforcement

Effect of longitudinal compressive reinforcement

In order to reflect the effect of longitudinal compressive reinforcements on the torsional strength of sample B and C were compared. The torque moment ratio (T/M) for each of the samples was adopted as 1, 2and 3. Two different percentages of compressive reinforcements - 0.2512 and 0.5024 were used keeping the tensile reinforcement as a constant value of 0.5024 percent (Refer Table 3.1). Data presented in the Figure show that at ultimate torque effect of longitudinal reinforcement is observed. It has been observed for λ=1 and 3 the effect of compressive reinforcement seems insignificant on ultimate torsional capacity for λ=2 in ultimate torsional capacity with the increment of tensile reinforcement.

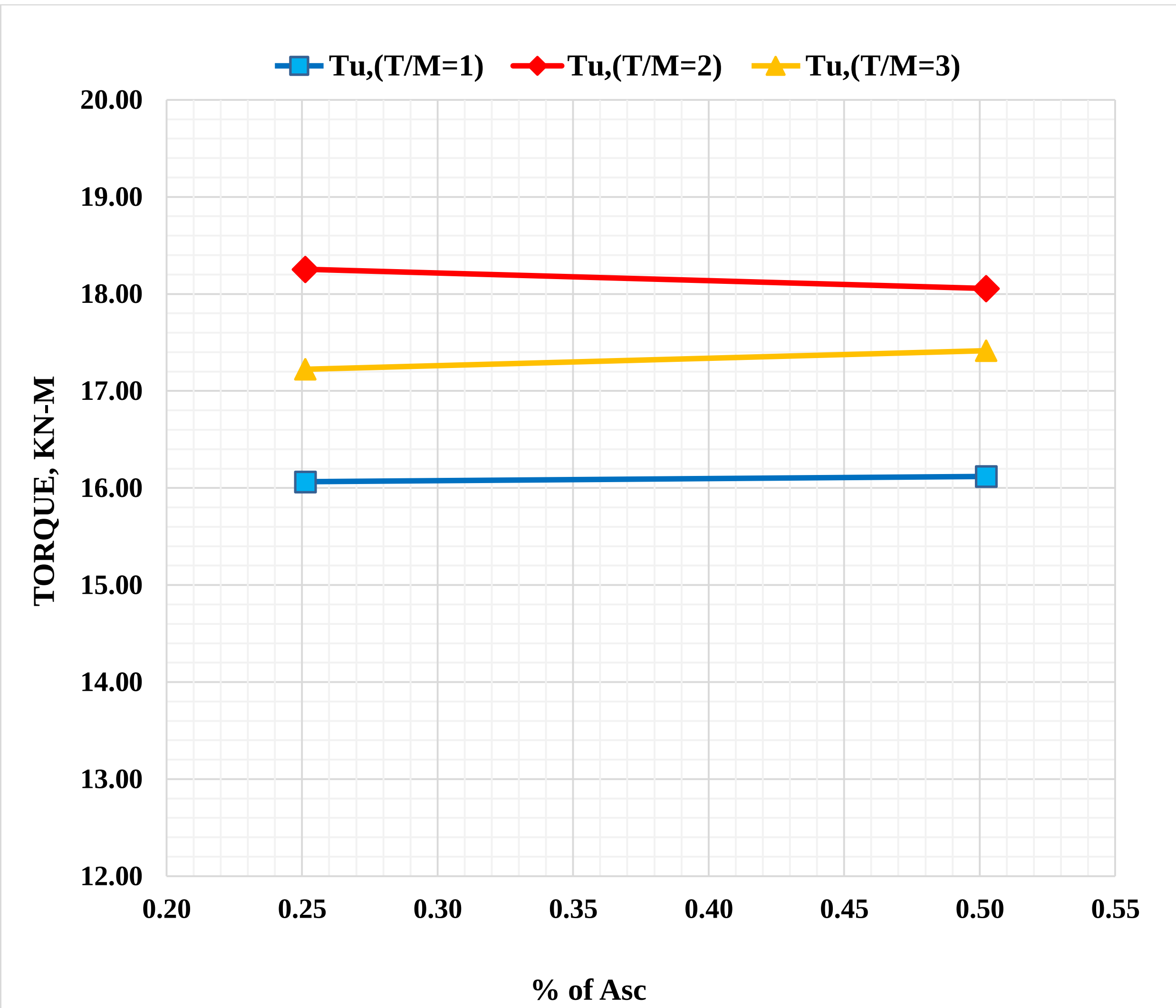

Figure 4.7 Effect of Longitudinal Compression Reinforcement

Effect of transverse to longitudinal reinforcement ratio (ρt / ρL) %:

In order to reflect the effect of longitudinal of transverse to longitudinal reinforcement ratio on the torsional strength the data of two different set of (ρt / ρL) for λ=1 ratio of 1,2 and 3 are used. Two different percentages of transverse to longitudinal reinforcement ratio (ρt / ρL): - 20.3% and 35.7% were used. The amount of longitudinal reinforcement spacing of stirrups is kept constant only diameter of stirrups is changed (Refer Table 3.2). It has been observed from figure_ that an increase in transverse to longitudinal reinforcement ratio (ρt / ρL): by 75.7% causes an increase in ultimate resisting torsional moment by about 5%,2%,8% for torsion moment ratio of λ=1,2 and 3 respectively.

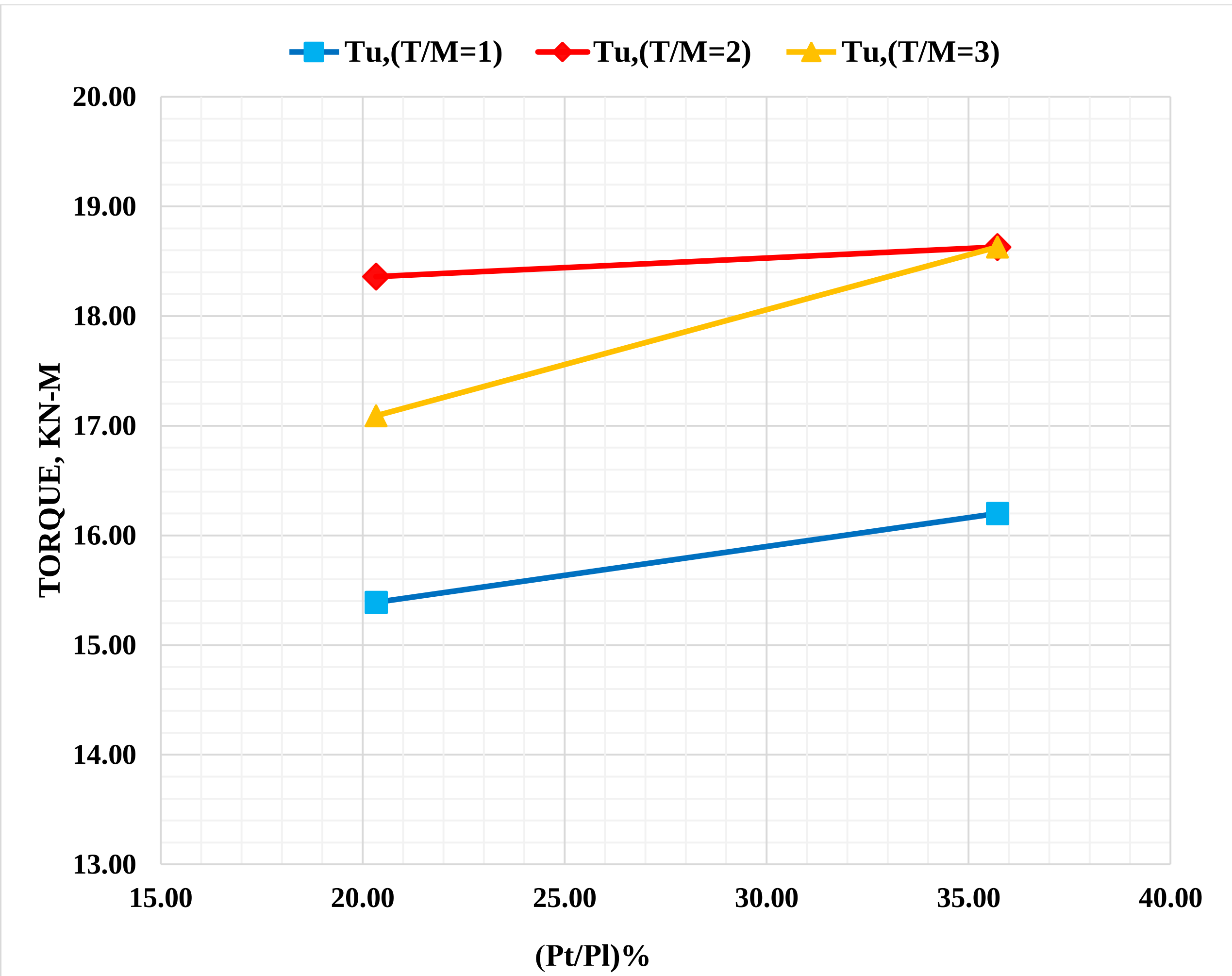

Figure 4.8 Effect of transverse to longitudinal reinforcement ratio

CHAPTER FIVE

CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusion

This research was aimed to study the behavior investigation on the strengthening of torsion critical member using carbon fiber reinforced polymer for different independent variables. These different independent variables were to be studied using the finite element method of analysis, which requires the generation of a model to predict the behavior of CFRP beams. The general-purpose finite element program ABAQUS was used to conduct the non-linear finite element analysis. Using ABAQUS, a model was created, as described in this paper, to predict the ultimate torsional resisting capacity. The created model was compared with existing results to verify the reliability of the generated model. It was found that the model generated was able to accurately predict the ultimate torsional load. By using generated model investigations are carried out on different parameters to fulfill the objective of this research. In total, fifteen different modeling schemes under two series were analyzed and graphed. The graphed results clearly depicted the behavior of CFRP strengthened beam for each independent variable. The following conclusions are drawn from the investigation:

- the nonlinear finite element studies showed that the ultimate strength of torsion critical CFRP Strengthened members are greatly affected by relative amount of longitudinal reinforcement, ratio of transversal and longitudinal reinforcement, pattern of distribution of longitudinal reinforcement and ratio of torsion to bending moment.
- The Effect of torsion to bending moment ratio (T/M) on ultimate strength of torsion is clearly observed as the reinforcement amount and distribution changes. As T/M goes from 1 and 2 the ultimate torsional strength increases and as T/M goes from 2 and 3 the ultimate torsional strength decreases
- With the increment of longitudinal Compressive reinforcement, no significant torsional strength improvement is seen. However, with the increment of tensile reinforcement ultimate torsional in general is found increased.
- For beams in which the area of tension steel exceeds that of the compression steel, the ultimate torsional capacity is increased more than for beams in which the areas of top and bottom steel are equal

- By comparing results of series 1 and series 2 model beams it is possible to conclude that only a proportional increment between transversal and longitudinal reinforcement improves ultimate torsional strength of beams.
- Provided that the above statement true and as long as premature failure is not occurring increasing transverse to longitudinal reinforcement ratio improves the ultimate torsional strength of beams significantly.
- Moreover, the study shows that during strengthening of torsion critical beams, attention should be given to the associated bending moment and the amount and distribution of reinforcements as they greatly affect the torsional strength improvement.

5.2 Recommendation

The thesis presented the capability of modeling torsion critical members under combined action using the proposed model. Regarding the proposed model and the nonlinear finite element packages, the following recommendations are advanced for future works.

- The proposed model should be further developed to include biaxial bending, biaxial shear, and axial force.
- The model is capable of predicting the ultimate strength, this study further be extended to ductility behavior under combined action
- Even though the proposed model works for wide range of parameters, this study should be extended under large cross section and high reinforcement ratio.

REFERENCES

1. Mohammed, S Strengthening Torsion Critical Reinforced Concrete Beam by Externally Bonded Carbon Fiber Reinforced Polymer Addis Abeba University 2018
2. Panchacharam S, Belarbi A. Torsional behavior of reinforced concrete beams strengthened with FRP composites. In First FIB Congress, Osaka, Japan 2002 Oct 13 (Vol. 1, pp. 01-110).
3. ACI Committee 318. Building Code Requirements for Structural Concrete and Commentary (ACI 318-99), American Concrete Institute, Detroit, MI, 1999.
4. Xanthakos PP, Bridge strengthening and rehabilitation: Prentice Hall PTR, 1996
5. HASHEMI SH, Rahgozar R, Maghsoudi AA. Flexural testing of high strength reinforced concrete beams strengthened with CFRP sheets
6. Tudu C. Study of torsional behaviour of rectangular reinforced concrete beams wrapped with CFRP (Doctoral dissertation).
7. Mohammadizadeh MR, Fadaee MJ, Ronagh HR, Ahmadinezhad A. Behavior of high-strength concrete beams strengthened with CFRP sheets in torsion. In FRP Composites in Civil Engineering: Proceedings of the 4th International Conference on FRP Composites in Civil Engineering, 22-24 July 2008, Zurich, Switzerland 2008.
8. Bakis C E., Bank, L. C., Brown, V. L., et al. Fiber-reinforced polymer composites for construction -state-of-the-art review, Journal of Composites for Construction. 2002; 6(2):73-87
9. Hag-Elsafi, O., Lund, R. and Alampalli, S. Strengthening of Church Street Bridge Pier Cap beam Using Bonded FRP Composite Plates: Strengthening and Load Testing. (Special report 138), Transportation Research and Development Bureau, New York. 2002.
10. ACI-440.2R-02. Guide for the Design and Construction of Externally Bonded FRP Systems for strengthening Concrete Structures. American Concrete Institute, Farmington Hills, MI 48333-9094. 2002.
11. De Lorenzis L,Teng, J. Near-surface mounted FRP reinforcement: An emerging technique for strengthening structures Composites Part B: Engineering. 2007; 38(2);119-143.
12. Panchacharam S, Belarbi A. Torsional behavior of reinforced concrete beams strengthened

with FRP composites. In First FIB Congress, Osaka, Japan 2002 Oct 13 (Vol. 1, pp. 01-110).

13. Ronagh HR, Dux PF. Full-scale Torsion Testing of Concrete Beams Strengthened with CFRP
14. Ameli M, Ronagh HR. Analytical method for evaluating ultimate torque of FRP strengthened reinforced concrete beams. Journal of Composites for construction. 2007 Aug;11(4):384-90.
15. Salom PR, Gergely J, Young DT. Torsional strengthening of spandrel beams with fiber-reinforced polymer laminates. Journal of Composites for Construction. 2004 Apr;8(2):157-62.
16. Rashidi M, Takhtfiroozeh H. The Evaluation of Torsional Strength in Reinforced Concrete Beam. Mechanics, Materials Science & Engineering Journal. 2017 Apr 14;7.
17. Mohammadizadeh MR, Fadaee MJ, Ronagh HR, Ahmadinezhad A. Behavior of high-strength concrete beams strengthened with CFRP sheets in torsion. In FRP Composites in Civil Engineering: Proceedings of the 4th International Conference on FRP Composites in Civil Engineering, 22-24 July 2008, Zurich, Switzerland 2008.
18. HASHEMI SH, Rahgozar R, Maghsoudi AA. Flexural testing of high strength reinforced concrete beams strengthened with CFRP sheets
19. Esfahani MR, Kianoush MR, Tajari AR. Flexural behaviour of reinforced concrete beams strengthened by CFRP sheets. Engineering structures. 2007 Oct 1;29(10):2428-44.
20. Dong J, Wang Q, Guan Z. Structural behaviour of RC beams with external flexural and flexural shear strengthening by FRP sheets. Composites Part B: Engineering. 2013 Jan 1;44(1):604-12
21. El-Gamal SE, Al-Nuaimi A, Al-Saidy A Al-Lawati A. Efficiency of near surface mounted technique using fiber reinforced polymers for the flexural strengthening of RC beams. Construction and Building Materials. 2016; vol. 118:pp. 52–62
22. Tudu C. Study of torsional behaviour of rectangular reinforced concrete beams wrapped with CFRP (Doctoral dissertation).
23. Jariwala VH, Patel PV, Purohit SP. Strengthening of RC beams subjected to combined torsion and bending with CFRP composites. Procedia Engineering. 2013 Jan 1;51:282-9.

24. Santhakumar R, Dhanaraj R, Chandrasekaran E. Behaviour of retrofitted reinforced concrete beams under combined bending and torsion: A numerical study. Electronic Journal of Structural Engineering. 2007;7:1-7.

25. Ersoy, U., and Ferguson, P. M. Behavior and strength of concrete L-beams under combined torsion and shear.Proc., ACI Journal Proceedings, ACI.

26. Aryal, M. P. Longitudinal reinforcement in concrete beams in torsion. Proc., 2005 International Congress -Global Construction: Ultimate Concrete Opportunities, July 5, 2005 - July 7, 2005, Thomas Telford Services Ltd, 579-586

27. Victor, D. J., and Ferguson, P. M. Reinforced concrete T-beams without stirrups under combined moment and torsion. Proc., ACI Journal Proceedings, ACI.

28. Mizra, M. S., and McCutcheon, J. O. Response of concrete beams with longitudinal reinforcing to combined bending and torsion. Engineering Journal, 1968,51(4), -.

29. Hsu, T. T. C. 1968. Torsion of structural concrete-plain concrete rectangular sections. 1968,ACI Structural Journal, 18, 203-238.

30. Ramakrishnan, V., and Vijayarangan, B. The influence of combined bending and torsion on rectangular beams without web reinforcement. Indian Concrete Journal, 1963,412-416.

31. Gesund, H., Schuette, F.J., Buchanan, G.R., Gray, G.A. Ultimate strength in combined bending and torsion of concrete beams containing both longitudinal and transverse reinforcement. Journal of the American Concrete Institute. 1964. 61(12). Pp. 1509–1522

32. Mahmood, M. N. Nonlinear analysis of reinforced concrete beams under pure torsion. Journal of Applied Sciences, 2007, 7(22), 3524-3529

33. Mostofinejad, D., and Talaeitaba, S. B. (2011). Nonlinear Modeling of RC Beams Subjected to Torsion using the Smeared Crack Model." Procedia Engineering, 14(0), 1447-1454.

34. Lisantono, A. Nonlinear finite element analysis of torsional R/C hybrid deep Tbeam with opening. Computers and Concrete, 2013, 11(5), 399-410.

35. Al-Rousan, R., Abo-Msamh, I., Bending and torsion behavior of CFRP strengthened RC beams Magazine of Civil Engineering. 2019. 92(8). Pp. 48–62

36. Hsu, Thomas T. C., Torsion of Structural Concrete - Behavior of Reinforced Concrete

Rectangular Members, Torsion of Structural Concrete, SP-18, American Concrete Institute, Detroit, 1968, pp. 261-306.

37. Collins, M.P., Walsh, P.F., Archer, F.E., and Hall, A.S., The Ultimate Strength of Reinforced Concrete Beams Subjected to Combined Torsion and Flexure, American Concrete Institute Special Publication, SP-18, 1968, pp. 379-402.
38. Collins, M.P. and Lampert, P., Torsion, Bending and Confusion - An Attempt to Establish the Facts, Journal of the American Concrete Institute, Vol. 69, No. 8, August 1972, pp. 500-504.
39. Mitchell, D. and Collins, M.P., Influence of Prestressing on Torsional Response of Concrete Beams, Journal of the Prestressed Concrete Institute, Vol. 23, No. 3, May-June 1978, pp. 54-73.
40. S. W. Tsai. Strength theories of filamentary structures. Wiley Intercedence, New York, 1968.
41. S. W. Tsai and E. M. Wu. A general theory of strength for anisotropic materials. Journal of composite materials, 5(1):58{80, 1971.
42. Z. Hashin. Failure criteria for unidirectional fiber composites. Journal of applied mechanics, 47(2):329{334, 1980.

Appendix A Mechanical properties

Compressive stress vs Total strain

Strain	Stress
0	0
0.0001	2.837
0.0002	5.648
0.0003	8.409
0.0004	11.09
0.0005	13.688
0.0006	16.166
0.0007	18.516
0.0008	20.724
0.0009	22.780
0.001	24.680
0.0011	26.420
0.0012	27.999
0.0013	29.419
0.0014	30.685
0.0015	31.801
0.0016	32.776
0.0017	33.615
0.0018	34.329
0.0019	34.925
0.002	35.413
0.0021	35.801
0.0022	36.098
0.0023	36.312
0.0024	36.452
0.0025	36.525
0.0026	36.538
0.0027	36.266
0.0028	36.053
0.0029	35.500
0.003	34.500
0.0031	33.000

Inelastic Stress vs inelastic strain

Yield stress	Inelastic strain
10.67	0
13.68784529	1.82033E-05
16.16644612	3.09593E-05
18.51584954	4.8263E-05
20.72357403	7.05535E-05
22.78036836	9.81567E-05
24.68013643	0.000131287
26.41975044	0.000170055
27.99877849	0.000214475
29.41915421	0.000264479
30.68481455	0.000319929
31.80132852	0.000380629
32.77553573	0.000446338
33.61520874	0.000516783
34.3287486	0.000591667
34.92491921	0.000670682
35.41262239	0.000753516
35.80071325	0.000839855
36.09785364	0.000929396
36.31239985	0.001021844
36.45232072	0.001116919
36.52514147	0.001214356
36.53790918	0.001313907
35.6	0.0015
33.5	0.00165
33	0.0017

Compressive Damage parameter Vs Crushing Strain

Damage parameter	Inelastic strain
0	0
0.007501375	0.000285147
0.013332322	0.000506798
0.019163269	0.000728448
0.024994217	0.000950098
0.030825164	0.001171748
0.036656111	0.001393398
0.042487058	0.001615048
0.048318005	0.001836698
0.054148952	0.002058348

Cracking Stress vs Cracking Strain

Yield stress	Inelastic strain
3.75	0
3.5	0.00008
2.8	0.000304
1.68	0.0006624
0.672	0.00098496
0.2016	0.001135488

Tensile Damage parameter Vs Cracking Strain

Damage parameter	Cracking Strain
0	0
0.067	0.00008
0.2	0.00024
0.4	0.00048
0.6	0.00072
0.8	0.00096