NUMERICAL ANALYSIS OF RC BEAM TO ENHANCE THE TORSIONAL RESISTANCE WITH CFRP

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A thesis submitted to the Department of Civil Engineering in partial fulfillment for the degree of Bachelor of Science in Civil Engineering

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Dedicated

to

“Our parents”

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ABSTRACT

This research numerically represents the technique of increasing torsional strength of reinforced concrete (RC) beam using Carbon fiber reinforced polymer (CFRP) under pure torsion. Many researchers worldwide have extensively used fiber-reinforced polymer (FRP) strengthening materials to enhance the shear and flexural strengths of reinforced concrete RC beams. However, studies on torsional strengthening are limited. FRP laminate can be used as external reinforcement for the reintegration of RC structures and due to their high tensile strength and corrosion resistance, they are preferable over steel plates. This study aims at demonstrating the behavior of RC beams under pure torsion strengthened with CFRP sheets with different configurations. Total 4 beams are modeled with the dimension of (150x230x1500) mm. One of them is performed as a control beam and others are configured with different orientations of FRP sheets which are: fully wrapped, 90^0 vertical wrapped strips, 45^0 inclined wrapped strips. Ultimate torque, angle of twist, ultimate load and cracking angle has been measured from the numerical analysis. It is seen that CFRP performed better to increase the torsional strength compared to the control beam. Fully CFRP wrapped beam has increased the ultimate torque and ultimate load-carrying capacity by about 75.28% and 90^0 Vertical CFRP wrapped strip beam has decreased the maximum amount of angle of twist which is 66.33%. 45^0 Vertical CFRP wrapped strip beam gives the optimum results between fully wrapped and 90^0 Vertical CFRP wrapped strip beams. Finally, these results have been validated with the experimental result available in the literature and analytical calculation. Numerical study has been carried out by using Finite Element Software, ABAQUS to bring into focus the versatility and powerful analytical capabilities of finite element techniques by objectively modeling the complete response of beams.

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CHAPTER 1

INTRODUCTION

1.1 General

Concrete is a structural material consisting of hard, chemically inert particulate substances, known as aggregate (such as sand, gravel, etc.) that is bonded together by cement and water. Concrete is relatively brittle, and its tensile strength is typically only about one-tenth of its compressive strength.

To increase the tensile strength of concrete, Joseph Monier, a Parisian gardener invented reinforced concrete which has been hardened onto embedded metal (usually steel). Reinforced concrete is also known as ferroconcrete. Nowadays in some practices concrete is reinforced with a small number of different types of random fibers to increase the crack control parameter of concrete, toughness, and energy absorption capacity of the materials. Day by day this practice becomes popular.

Fibers are mixed with concrete as a percentage of the total volume of concrete and when concrete with fiber is hardened, this allows the concrete to resist a considerable amount of crack when bodies are subjected to different kinds of loading.

Figure 1 shows how the percentage of fibers affects the net deflection with the increasing load.

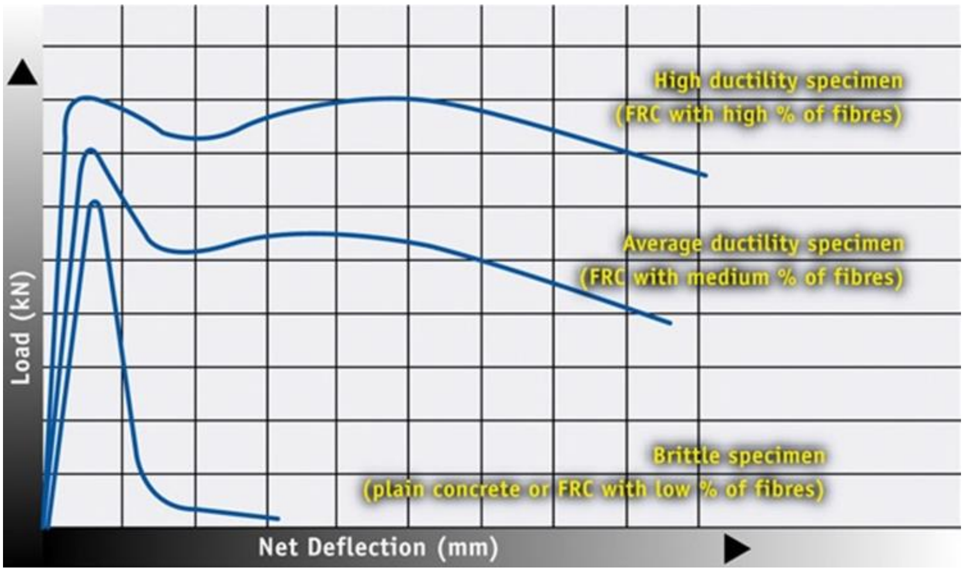
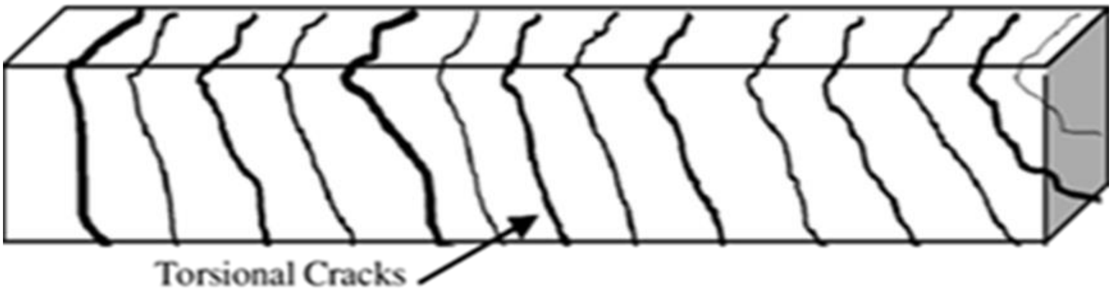
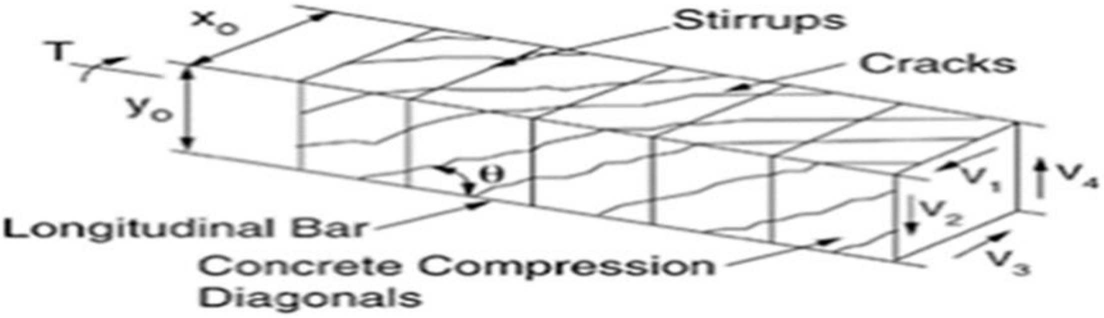


Figure 1.1: Load-Deflection Curves with different fiber percentage

Beams located at the perimeter of the building, when they subjected to the loads coming from the slab, a torsional force is generated there which tends to twist the beam with different angle of twist in either side. For the effect of a considerable amount of angle of twist between the material, cracking may happen there. To resist this kind of cracking effect, a Fiber Reinforce Polymer system is present nowadays. Using Fiber Reinforce Polymer (FRP), it can be possible to control the cracking behavior of the RC beam at its post-cracking stage.



(1) Source: (https://images.app.goo.gl/sDVC8uFYmikSJTPQA, Accessed 11 July,2022)



(2) Source: (https://images.app.goo.gl/yDeMNM4nwd7vFmpn8, Accessed 11 July,2022)

Figure 1.2: (1),(2) Torsional cracks

weight ratio, non-corrosiveness. These characteristics make FRP the most effective material for increasing crack control phenomena and torsional resistance, repair, and rehabilitation of deficient RC structures. Different Kinds of research potential on FRP have arisen since the '90s, 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 the 1980s, several researchers initiated using FRP in civil engineering applications as a separate research domain to explore properties of FRP and highlighted typically two main fibrous materials like glass and carbon to strengthen structural members. 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. However, E-glass fibers are comparatively not much stronger and stiffer than S-fibers.

Figure 1.3 shows the general behavior of FRP in comparison to steel under tensile stresses, from the stress-strain relationship figure it is clear that the stiffness of CFRP is higher than GFRP and steel. CFRP and GFRP are used in the high level of reinforced concrete strengthening applications. Some of the typical material properties of CFRP have been shown in Table 1.1

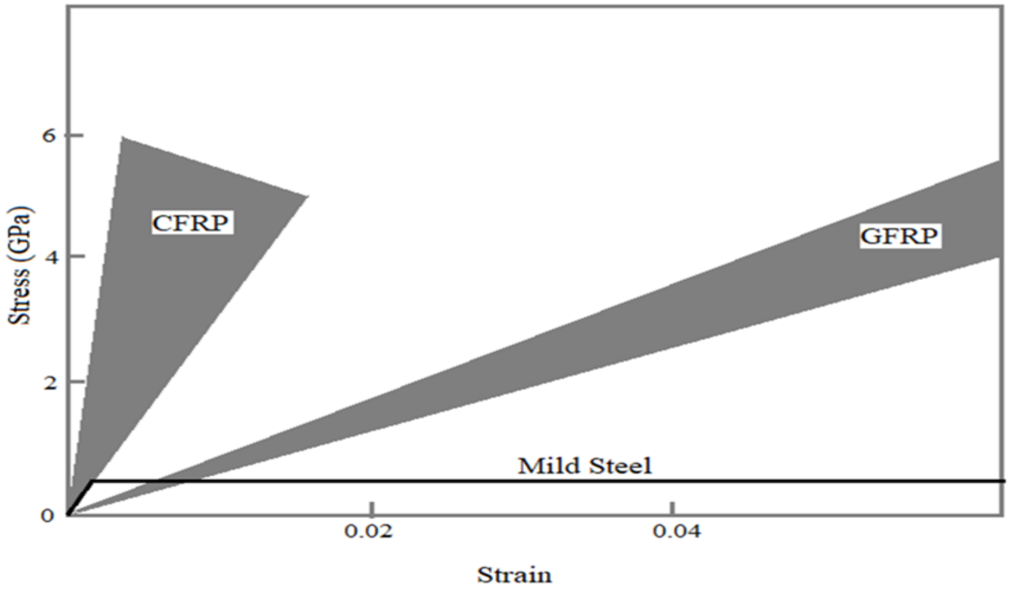


Figure 1.3: Typical stress-strain relation for different FRPs and normal steel

(Source : https://images.app.goo.gl/ZnfC8t9ekZmJUPRQ9, Accessed 11 July,2022)

In this study carbon fiber (CFRP) is used for strengthening of RC beam to withstand the cracks develop for the twisting effect of RC beams, because CFRP of overhauled on other FRPs comparative to other FRP.

Table 1. 1: Some Typical Properties of Carbon Fibers

Type of Fiber	Thickness (mm)	Ultimate Tensile Strength (MPa)	Elastic Modulus (GPa)	Ultimate Tensile Elongation (%)
Carbon	0.10-0.25	2100-6000	215-700	0.2-2.3

Fiber Reinforced Polymer (FRP) as a reinforcement element is used extensively to address the strength requirements related to flexure and shear in structural members. But the strengthening of members subjected to torsion is yet to be explored. In this Study, the behavior and performance of reinforced concrete beam strengthened with bonded fibers especially with Carbon fibers (CFRP) subjected to pure torsion is presented.

1.2 Historic Development of Fiber Reinforced Concrete

The concept of using fibers to increase the tensile strength is more than 4500 years old. Mesopotamian civilizations used straw fibers in sun-dried mud bricks in order to create a composite with increased toughness. This works as a matrix with better resistance to cracking and an improved post cracking response. When ordinary Portland cement concrete started to be used widely as a construction material many more attempts were made to use fibers for controlling cracks. Engineers had to overcome the major deficiencies of concrete, which were the low tensile strength and the high brittleness. A French engineer, named Joseph Monier, in 1847 came out with the idea of adding continuous fibers into the concrete, in the form of wires or wire meshes. This led to the development of ferrocement, and reinforced concrete as known today. The use of continuous steel reinforcing bars in the tensile zone of concrete undoubtfully helped to overcome the problem of the low tensile strength of concrete. However, the idea of using discontinuous fibers in the concrete was always a challenge.

1.3 Behavior of RC Beam Subjected to Torsion

In the past few decades, the interest in gaining a better understanding of the torsional behavior of reinforced concrete (RC) members has increased. This might have happened because of the increase of such structural members in which torsion is the central feature of behavior, Ex-helical slab, curved bridge girders, etc. However, the achievement in the case of torsion is not as satisfactory as shear and bending.

Now if the external loads act far away from the vertical plane of bending, the beam is subjected to twisting about its longitudinal axis, known as torsion. A torsional moment in the beam is accompanied by a bending moment and shearing force. When the resultant force of the beam passes through its longitudinal shear center axis, the beam only bends and no torsion occurs, but if resultant forces act away from the shear center axis, the beam is subjected to both bending and twisting.

Under normal conditions, the RC beam is designed for flexural and shear. The torsional effect is normally neglected most of the time by providing adequate sectional depth and reinforcement in the region where shear stress is affected mostly to avoid undesirable situations. Under a different scenario, this neglecting effect of torsion required to reimburse by designing a new system for strengthening the RC beam, which is not only contributing to flexural and shear but also torsion. Torsion transpires very frequently in all structures especially in bridges, but hardly ever reveals pure torsion in any structure.

Most of the working studies are limited to pure flexural failure, shear failure, or both analytically and experimentally. Pure torsional effects have been observed under most of the experimental studies which do not support another failure. However, torsion is one of the essential structural actions besides flexural and shear. Torsion is the twisting of a structural member loaded by torque, or twisting couples. The twisting or turning in a beam is caused by forces tending to turn one end or part of the beam about its longitudinal axis, while another side of the beam is fixed or twist in opposite direction. During designing, beams are loaded in such a way that the effect of torsion is neglected, however, most of the time torsion in the beam is caused by the eccentric loads. When the RC beam is subjected to torsion, then it exhibits cracks due to torsional shear stresses which cannot resist by concrete alone, and another mechanism such as steel required resisting the loads. But the continuous increase of load on the beam required another mechanism to resist this combined torsion and bending effects then the strengthening of the beam is required.

1.4 Characteristics of Fiber Reinforced Polymer (FRP)

Fiber Reinforced Polymers (FRP) are unique composite materials in many respects. FRP can be formulated to be corrosion, abrasion, and UV resistant, as well as, smoke and fire retardant. FRP is often a cost-effective choice in many industrial applications; they have long life cycles and have demonstrated durability in extreme environments with reduced maintenance costs.

Here are some of the characteristics of Fiber Reinforced System.

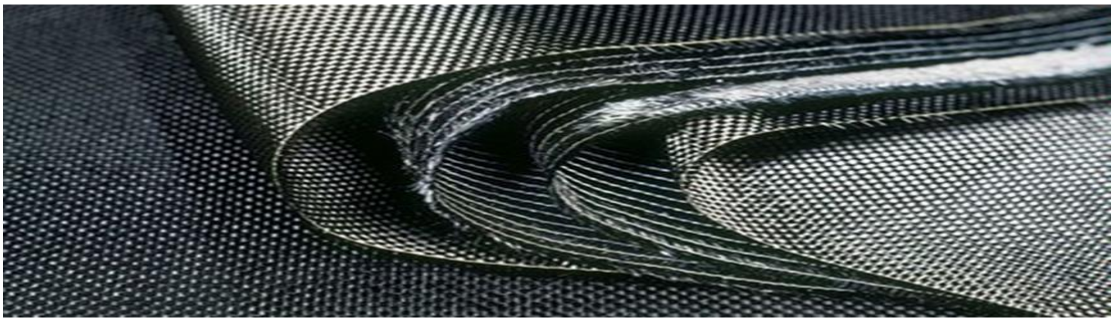
- High Strength-to-Weight Ratio– FRP is lightweight and strong; they possess a vast range of mechanical properties, including tensile, flexural, impact, and compressive strengths. Compared to other metals they have more strength per unit of weight than most metals. Their lightweight also helps in easy shipment and installation.
- Customizable- Every industry has unique problems to solve. With FRP engineers have the ability to tailor or modify the design of their FRP to meet their specific requirements.
- Anisotropic- Engineers can maximize the performance and efficiency of the structure when they take advantage of the inherent anisotropic properties of FRP. Because the maximum strength is in the direction of the fiber reinforcement's engineers can optimize the design to optimize the materials and the overall performance of the structure.
- High Tensile Strength with Low Modulus of Elasticity-FRP has high tensile strength due to its composite properties. Engineers can specify unique resin, fiber-reinforcement compositions when working with FRP manufacturers. The design control inherent to FRP will enhance performance and can only be realized when working with composites, not metals.
- Ability to Form Complex Shapes- Engineers can harness ultimate design flexibility when using FRP—an advantage over traditional materials such as metal, concrete, and wood.

1.5 Types of FRP Composites

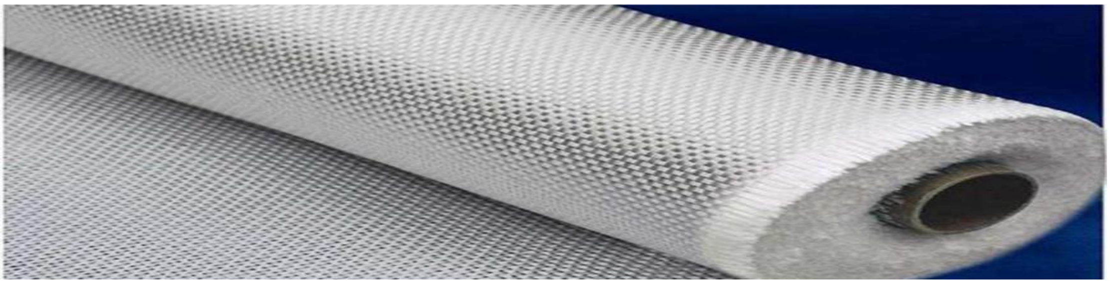
There are many types of FRP composites are used now a days for strengthening the normal RC beam. Among of them these FRP composites are very common. Which are:

- Carbon fiber reinforced concrete (CFRP)
- Glass fiber reinforced concrete (GFRP)
- Aramid fiber reinforced concrete (AFRP)

Aramid Fiber (Source: https://images.app.goo.gl/JHMv1dXmEHUdUSiKA, Accessed 11 July,2022)



Carbon Fiber (Source: https://images.app.goo.gl/fS8toREfWzKbLYHN8, Accessed 11 July,2022)



Glass Fiber (Source: https://images.app.goo.gl/AoYzkYpyaazfqSNJA, Accessed 11 July,2022)

Figure 1.3: Different Fiber Polymer Composites

1.6 CFRP (Carbon Fiber Reinforced Polymer)

Carbon fiber reinforced polymers are composite materials that rely on carbon fiber to provide strength and stiffness while the polymer provides a cohesive matrix to protect and hold the fibers together and provides some toughness. Carbon fibers provide highly directional properties much different than the metals most commonly used for these automotive applications. They can be engineered to achieve mass reductions not achievable by the metals. Since these are artificially composited materials their properties and performance can be tailored to the application through varying strength, length, directionality, and amount of the reinforcing fibers and in the selection of the polymer matrix. The largest drawbacks are the high cost of producing the fibers and the low throughput rates at which components can be manufactured. The cumulative time to place the fibers in a mold, inject the polymer, and allow the part to set is in the order of a few minutes.

Carbon Fiber Reinforced Polymer (CFRP) is composed of carbon fibers embedded in a polymer resin in which the carbon fibers function as the reinforcement material and the polymer resin functions as the matrix to hold the fibers. The typical structure of CFRP can be illustrated in Figure 2.

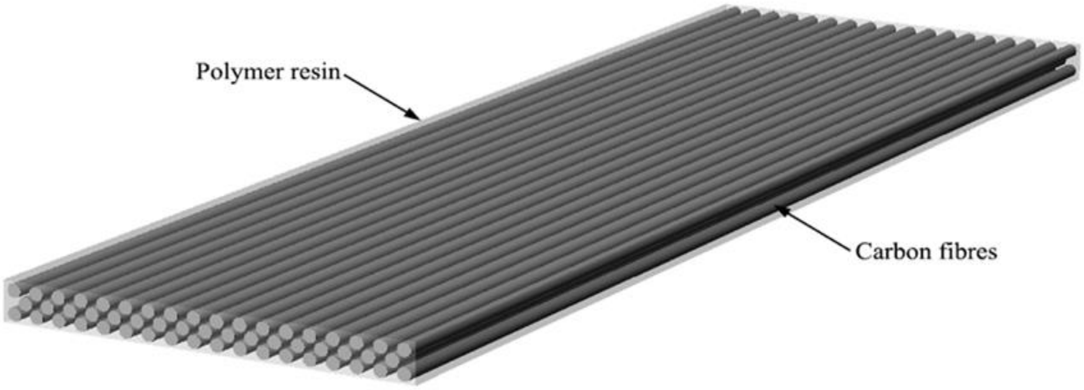


Figure 1.4: Typical structure of Carbon Fiber Reinforced Polymer (CFRP)

(Source: https://images.app.goo.gl/MbyenB38dUUjt1jh6, Accessed 11 July,2022)

Some properties of CFRP composite materials, which are advanced composite materials, like high load-bearing capacity, low density, high toughness, low damage tolerance, high strength, high hardness, lightness, low frictional coefficient, good wear resistance, chemical and dimensional stability, corrosion resistance, low electric resistance and vibration damping properties make them preferable.

1.7 The Objective of the Research

The objectives of the investigation are:

- To model an RC beam using ABAQUS software and make a Finite Element (FE) analysis.
- To investigate the performance of CFRP to increase the torsional strength using the FE analysis
- To investigate the effective orientation of FRP composites using the FE analysis.
- To examine the failure patterns of RC beams made configured with CFRP using the FE analysis.

- To Compare the FE analysis result with available literature results and analytical calculations.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

Most of the research projects investigating the use of FRP focused on enhancing the flexural and shear behavior, ductility, and confinement of concrete structural members. A limited number of mostly experimental studies were conducted to investigate the torsion strengthening of RC members. There is some research conducted over two decades on the torsional strengthening of RC beams using Fiber Reinforced Polymer (FRP), they are discussed below.

2.2 Previous Background of the Study

(Tibhe & Rathi, 2016) used Fiber-reinforced polymer (FRP) as external reinforcement. FRP is used extensively to enhance the strength requirement related to flexure and shear and the strengthening of members subjected to torsion in structural systems. Torsion failure is a brittle form of failure. From the experimental work, it was observed that using CFRP and GFRP, the torsional moment taking capacity was increased by 60.47% and 47.46% with respect to the control beam. Using different types of mixing patterns, the maximum increase in torsional moment capacity of the CFB beam was found 101.8% and the GFB beam was 83.49%. Also, the minimum increase in torsional moment capacity of the CFB beam was 40.02 % and 8.76 for the GFB beam. Compared to CFRP bonded RC beam with GFRP bonded RC beam, experimentally it proved that the CFRP fabric having maximum torsional strength than the GFRP fabric. This experimental work stated that CFRP and GFRP failure may be due to deboning of CFRP and GFRP or crushing of concrete. Crack width decreased due to the use of CFRP and GFRP fabric. This is a huge advantage of using CFRP and GFRP compared to ordinary reinforced concrete.

The ductility of the member also increased due to CFRP and GFRP. The ductility factor for the control beam was 0.055 whereas 0.085 for CFRP used beam and 0.076 for GFRP used beam which was the maximum value. It is more efficient than using a fully wrapped U- jacketed beam for both CFRP and GFRP to increasing in torsional strength.

The angle of twist was found maximum for the CFRP used beam, and minimum for control beam the angle of twist for carbon fiber fabricated beam, glass fiber fabricated beam and control beam was found 0.063, 0.053 and 0.0473 respectively. From the experiment, it can be concluded that the torsional strength, angle of twist, ductility factor was found maximum value for CFRP bonded beam than GFRP bonded beam.

(Jariwala et al., 2013) conducted their experiment only using GFRP used beams. Failure behavior using different fiber amounts was compared with the control beam which was the ordinary reinforced beam.

The study showed that in control beams vertical flexural cracks first appeared at the middle and then inclined diagonal tension cracks were generated and propagated in a spiral pattern. The cracks gradually widened as load increased with the two beam segments rotating relative to one another about the centroidal axis of the RC beam along with bending. Failure of beams using fibers was observed from the edge of the central portion of the beam specimen. Inclined diagonal cracks were observed inside the wrapping. Sudden failure of RC beam was observed after the generation of the first crack in fiber. The failure was partially delayed compared to control specimens.

The results of the experimental work found an increase in ultimate torsional strength, angle of twist at first crack, and ductility of the beam when a combination of GFRP placement pattern in the longitudinal direction followed. In the strengthening of RC beam with GFRP, diagonal strip wrapping is more efficient in resisting torsional moment compared to vertical strip. Test beam with corner and Diagonal strip wrapping exhibited a maximum (110%) increase in cracking torque and maximum (117%) increase in ultimate torque, compared to control beam among all the test beams.

(Imran et al., 2010) Worked to strengthened RC beams for flexure, shear, and torsion using only Carbon Fiber Reinforced Polymers (CFRP). Carbon Fiber Reinforced Polymers (CFRP) are the most widely and suitable strengthening technique. These experimental works were conducted with a number of CFRP strips to improve flexural strength, shear, and torsion behavior. Results found that inclined CFRP wraps are best suitable to improve flexural strength, shear, and torsion behavior. The study revealed that torsional resistance can be strengthened by increasing no. of CFRP strips in the tension zone. Torsion strengthening is possible with 45° CFRP wraps. Therefore, in order to strengthen the beam exhibiting flexure, shear, and torsional behavior together, the combined use of CFRP strip and wraps might be a suitable strengthening scheme; however experimental work is required for refinement and validates the suggestion.

(Askandar and Mahmood, 2019) used various CFRP wrapping configurations and NSM steel bar to conduct their experiment which was focused on the torsional behavior of RC beams strengthened under the combined effect of torsion and bending. Despite the CFRP wrapping configurations and NSM steel bar spacing, higher torsional resistance than that of the control beam was observed for all strengthened beams.

Beams with CFRP wrapping showed better enhancement in the ultimate torsional moment as opposed to the beams that were strengthened with NSM steel bar and control beams. The percentage of enhancement in the ultimate torsional moment (Tu), with respect to control beams was found 134%, 103%, and 85% for 3 different beams using CFRP. While this percentage for beams using NSM steel bar was found 44%, 37%, and 33%, respectively.

Ductility of all the CFRP-strengthened beams increased; while it decreased for NSM steel bar strengthened beams. Percentage of enhancement in ultimate twist angle (θu), with respect to the control specimen for CFRP, used beams found 120%, 118%, and 92%, respectively. While the percentage of enhancement in ultimate twist angle (θu), with respect to the control specimen for NSM steel bar, used beams found 17%, 24%, and 27%, respectively.

Cracks in the strengthened beams spread more extensively along their length compared with the singular cracks that formed in the control beam. Failure in the concrete beams was delayed when the CFRP strip and NSM steel bar were used to strengthen the beams. However, this delay unavoidably occurred in the unwrapped spaces between strips (for CFRP-strengthened beams) and spaces between NSM steel bar grooves (for NSM steel bar-strengthened beams). The experimental values for the control beam and CFRP-strengthened beams were in good agreement with the predictive analytical one.

(Rashidi and Hana, 2016) worked to evaluate the torsional strength in the reinforced concrete beam using an ordinary reinforced concrete beam. The main objective of this experimental work is to increase the torsion strength using transverse and longitudinal reinforcement.

The study found that the ductility factor increased with an increasing percentage of reinforcement. The torsional strength and ductility of the sample with transverse and longitudinal bars had been increased by 95% and 50% respectively in comparison with the sample without reinforcement. The transverse bars played an important role in increasing the torsional strength of the beams compared to longitudinal bars. It should be noted that transverse bars or longitudinal bars lonely would not able to increase the torsional strength of RC beams and both of them can be essential for having good torsional behavior in reinforced concrete beams.

(Punam and Yendhe, 2018) compared carbon fiber reinforced polymer (CFRP) and glass fiber reinforced polymer (GFRP) experimentally to evaluate how these composites work on the torsional strengthening of RC beams. The objective of the experimental study is to evaluate and compare the effectiveness of the use of epoxy-bonded carbon and glass FRP fabrics with different configuration as external transverse reinforcement to under reinforced concrete beams with rectangular beams subjected to pure torsion. The applied CFRP and GFRP configurations were U jacked, vertical and diagonal strips with spacing, edge strips with vertical and diagonal stripes along the entire length of the beam.

From the results of the experiment, it can conclude that GFRP used beams show lesser fatigue life comparative to CFRP used beams. Carbon fiber had greater shear strength than glass fiber. The angle of twist was found slightly greater for glass fiber fabricated beams than carbon fiber fabricated beams which were 5% to 10%. CFRP was found stronger in torsion comparative to GFRP and control beam. The maximum ultimate torsional moment was found for CFRP which was 86% greater than the control beam and that was a maximum of 76% greater than the control beam for GFRP. GFRP did not contribute to flexural strength whereas CFRP increased the flexural strength. CFRP is effective in the strengthening of steel structures to resist higher loads. From the experimental data and results, experts can easily identify that using CFRP laminates and sheets that have strength and thickness to increase the overall strength of the structural member and can significantly increase the fatigue life of bridges and other structural systems.

2.3 Advantages and Disadvantages of Using CFRP

CFRP is the most common FRP material due to its good tensile strength and availability.

Advantages of CFRP composite are:

- **Lightweight**: carbon fiber reinforced polymer is a low-density material with a very high strength to weight ratio. Its weight is ¼th if the steel; which means it does not increase the weight and section of the structure.
- **Corrosion resistance:** Carbon fiber is one of the most corrosion-resistant materials available for construction**.**
- **Very low thermal expansion:** With respect to steel or aluminum, carbon fiber has less expansion or contraction in hot or cold weather.
- **High electric conductivity:** CFRP composites are excellent when it comes to conducting electricity.
- **Exceptional durability**: Compared to other metals, carbon fiber has enormous fatigue properties which means it won’t wear out under the stress of constant use.

There are also some disadvantages too. Which are:

- ❖ **Cost:** The price of carbon fiber reinforced polymer is too high.
- ❖ **High repair cost:** The repairing cost for CFRP is huge.
- ❖ **Manufacturing Time:** To manufacture CFRP it requires a lot of time.

Figure 2.1: Strengthening process of RC beam using CFRP composites

(Source: https://images.app.goo.gl/cRsk1ujQEaJLeSXZ9, Accessed 11 July,2022)

2.4 Background and Present State of The Problem

From the background work, it is seen that increasing torsional strength with CFRP isn’t done before. Every researcher worked with one orientation of FRP composites but in this present study, CFRP is used to increase the torsional strength with different orientations, and comparison has been made to find which orientation is better. Principle stress variation and crack patterns are also discussed in this study.

CHAPTER 3

METHODOLOGY

3.1 General

Usually, software packages for structural analysis have been developed on the basis of the finite element method (FEM). Utilization of the software packages has been increased due to advantageous provision for rapid and nearly exact analysis and for the other post-processing utilities. Complex geometrical structures can be modeled through finite element analyzing software with higher accuracy. Using these software’s are timesaving and provides a complete framework of the work before field experimental work. There are many finite elements analyzing software are available. Among them the available software for structural analysis is mentioned as follow:

- ABAQUS
- ANSYS
- ETABS
- SAP 2000
- GRASP
- STAAD-PRO
- ALGOR
- COSMOS
- MATLAB
- PATRAN

Among these, we used ABAQUS for the project because of its availability and popularity. It is easy to use and almost gives an accurate result.

3.2 Finite Element Analysis

The finite element method (FEM) is a used method for solving problems of engineering and mathematical models. It conducts with a particular numerical method for solving partial differential equations. It solves the deferential equations by two or three space variables. Engineers and especially in civil discipline can convert any topic related to physics problems to FEA. It can verify the mathematical model includes structural analysis, fluid dynamics, and heat transfer. Mainly FEM conducts by dividing a large system into smaller, make the large system into more simple parts that are called finite elements. System of algebraic equations results in by the finite element method formulation of a confined value problem. Simple equations that model these finite elements are assembled into a larger system of equations. Various methods from calculus are uses which conduct various methods to get the approximate solution by minimizing an associated error function. Engineers can identify the prediction accuracy of a complicated model. By conducting this, they find out the core problem.

Reinforced concrete is one of the most complex materials in finite element modeling due to complicated nonlinear behavior in tension and compression. The correct definition of materials in finite element method modeling, inelastic, and plastic behaviors as well as in compression and tension domains can have a great impact on the responses and outputs.

In this study, the damage plasticity model is used for concrete. The model is a plasticity-based, Continuation based damage model. The model assumes tensile cracking and compressive crushing of the concrete material are the main two failure mechanisms. Damaged plasticity characterized the uniaxial tensile and compressive response of concrete.

3.3 ABAQUS Software

Abaqus is a software application used for both the modeling and analysis of mechanical components and assemblies (pre-processing) and visualizing the finite element analysis result. Abaqus/Standard, a general-purpose Finite-Element analyzer that employs an implicit integration scheme (traditional) besides Abaqus/Explicit, a special-purpose Finite-Element analyzer that employs an explicit integration scheme to solve highly nonlinear systems with many complex contacts under transient loads. Abaqus is used in the automotive, aerospace, and industrial products industries and structural engineering. Users can define their own material models so that new materials could also be simulated in Abaqus. Abaqus also provides a good collection of Multiphasic capabilities, such as coupled acoustic-structural, piezoelectric, and structural-pore capabilities, making it attractive for production-level simulations where multiple fields need to be coupled. Abaqus was initially designed to address non-linear physical behavior; as a result, the package has an extensive range of material models such as elastomeric (rubberlike) and hyperplastic (soft tissue) material capabilities. Every complete finite-element analysis consists of 3 separate stages:

- Pre-processing or modeling: This stage involves creating an input file which contains an engineer's design for a finite-element analyzer (also called "solver").
- Processing or finite element analysis: This stage produces an output visual file.
- Post-processing or generating report, image, animation, etc. from the output file: This stage is a visual rendering stage.

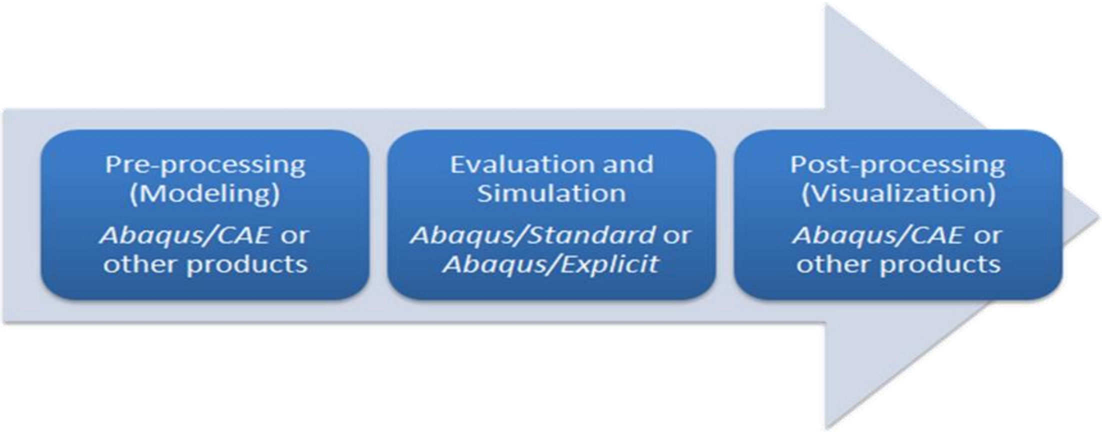


Figure 3.1: Finite element model solving steps

Abaqus/CAE is capable of preprocessing, post-processing, and monitoring the processing stage of the solver; however, the first stage can also be done by other compatible CAD software or even a text editor. Abaqus/Standard, Abaqus/Explicit or Abaqus/CFD can accomplish the processing stage.

3.4 Finite Element Model Development

In this research, a 3D finite model is developed to simulate the incensement of torsional strength of RC beam using CFRP and GFRP. Total 4 beam has been analyzed to determine the torsional strength which are:

- Normal RC beam
- RC beam with fully CFRP wrapped
- RC beam with 45^0 included CFRP wrapped strip

- RC Beam with 90^0 vertical CFRP wrapped strip

All the beam dimensions are the same (150x230x1500) mm and the same amount of reinforcement are used. A cantilever part is also constructed from a 75mm distance from the endpoint of the beam in opposite direction to provide a moment arm. The load cell is placed on the cantilever part which creates a pure torsion on the beam. The cantilever beam dimension is 150x230x400 mm.

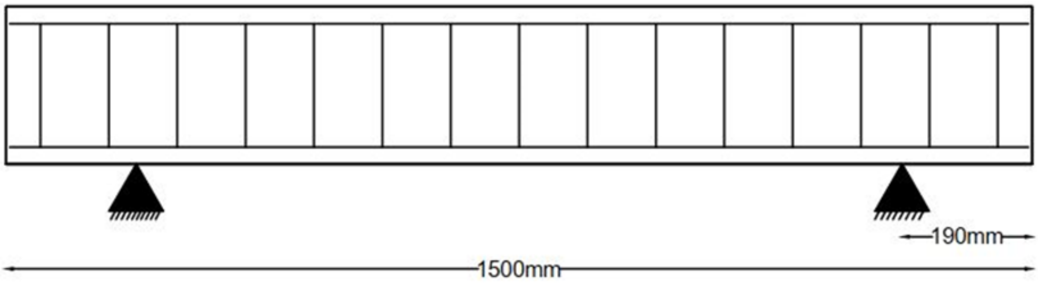


Figure 3.2: Designed beam longitudinal profile

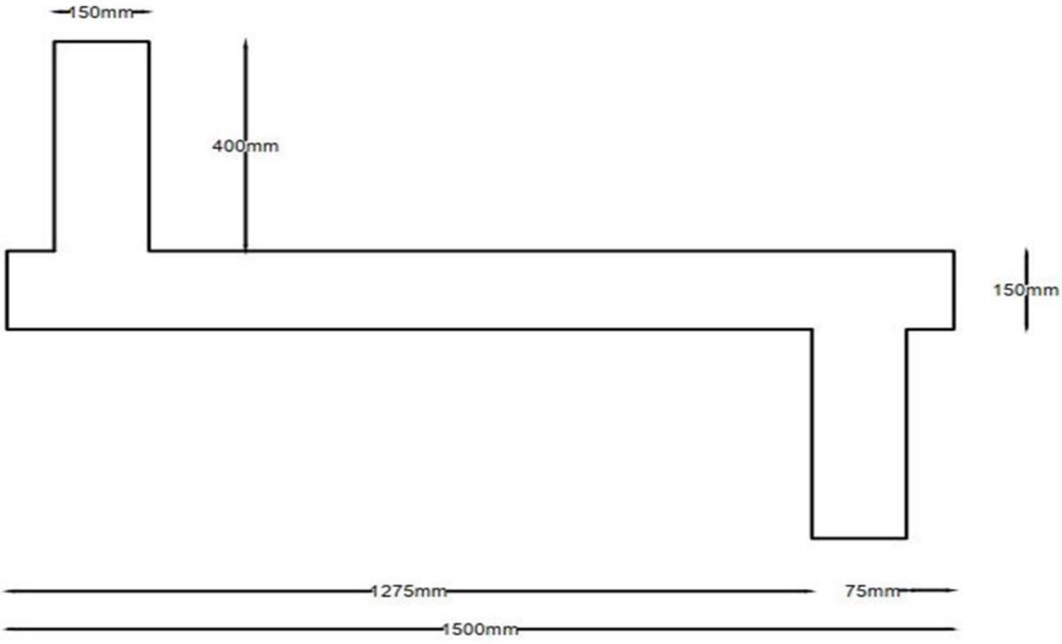


Figure 3.3: Designed beam plan view

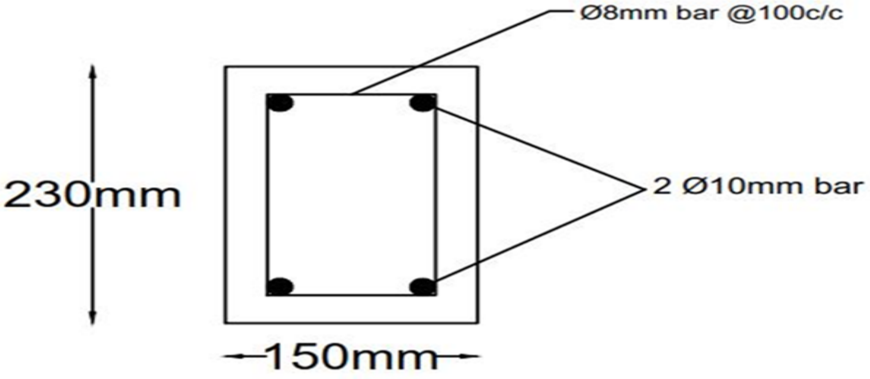


Figure 3.4: Main beam cross sectional profile

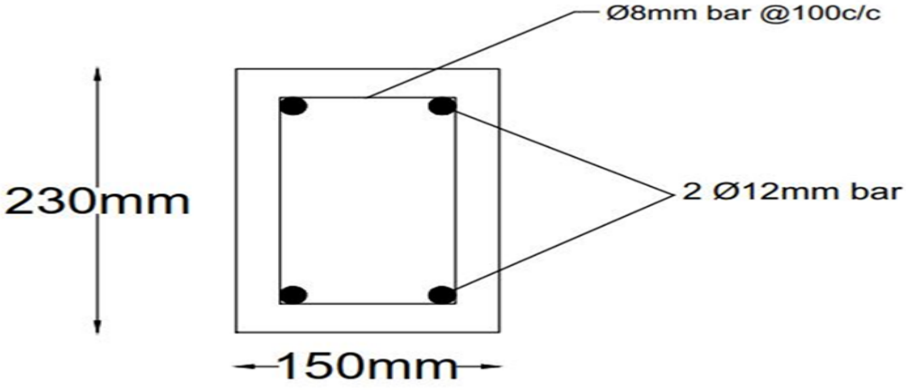


Figure 3.5: Cantilever beam cross-section profile

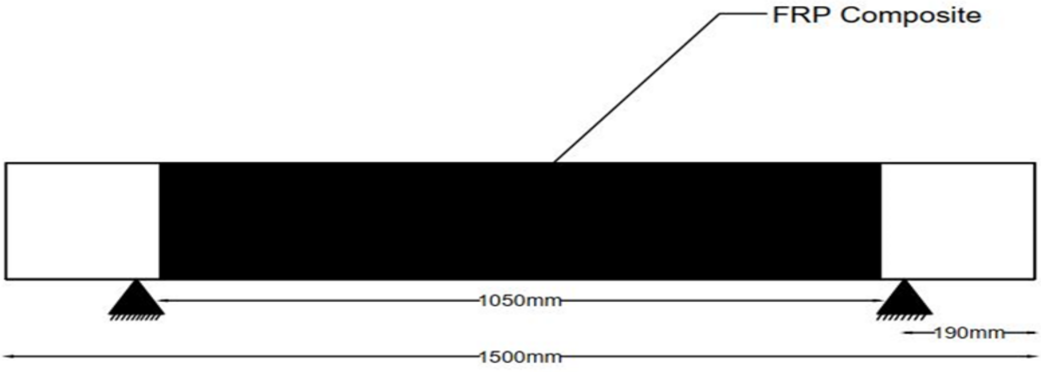


Figure 3.6: Designed RC beam with fully FRP wrapped

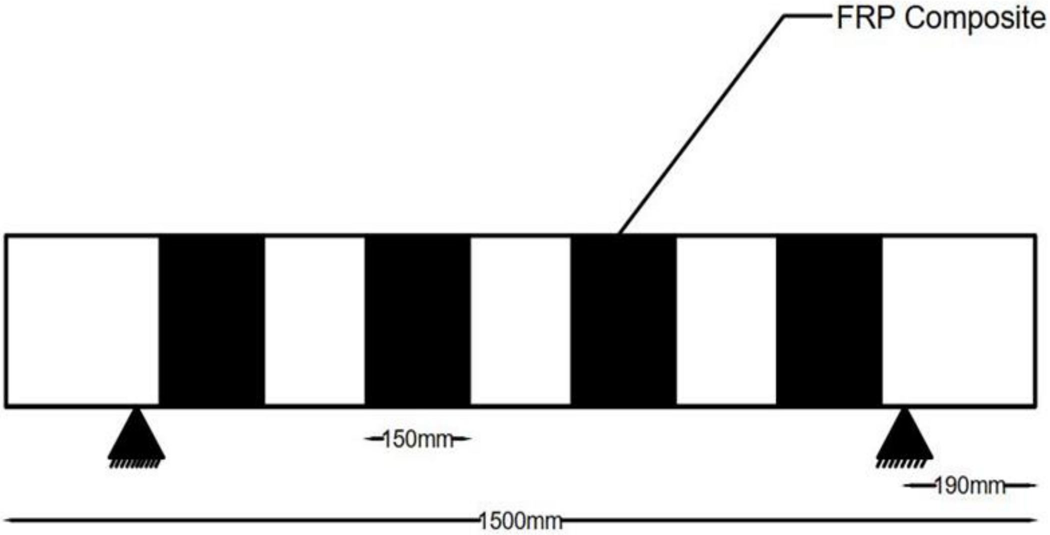


Figure 3.7: Designed RC Beam with 90°vertical FRP wrapped strip

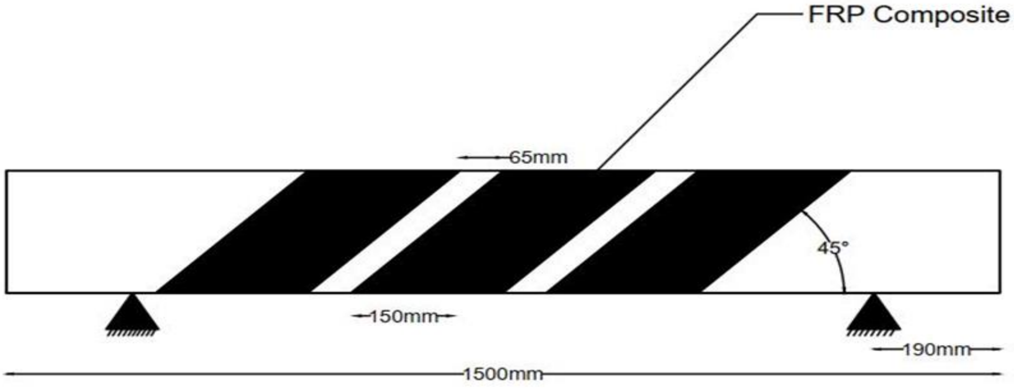


Figure 3.8: Designed RC beam with 45° inclined FRP wrapped strip

3.5 Material Properties of Modeling

For modeling in ABAQUS anyone have to define the material properties of the beam. The material used for modeling are:

- Concrete
- Reinforcement
- CFRP

3.5.1 Concrete

In compression, the stress-strain curve for concrete is linearly elastic up to about 30 percent of the maximum compressive strength. Above this point, the stress increases gradually up to the maximum compressive strength. After it reaches the maximum compressive strength σ_{cu} , the curve descends into a softening region, and eventually crushing failure occurs at an ultimate strain ε_{cu} . In tension, the stress-strain curve for concrete is approximately linearly elastic up to the maximum tensile strength. After this point, the concrete cracks and the strength decreases gradually to zero. Figure (3.9) shows typical uniaxial compressive and tensile stress-strain curve for concrete.

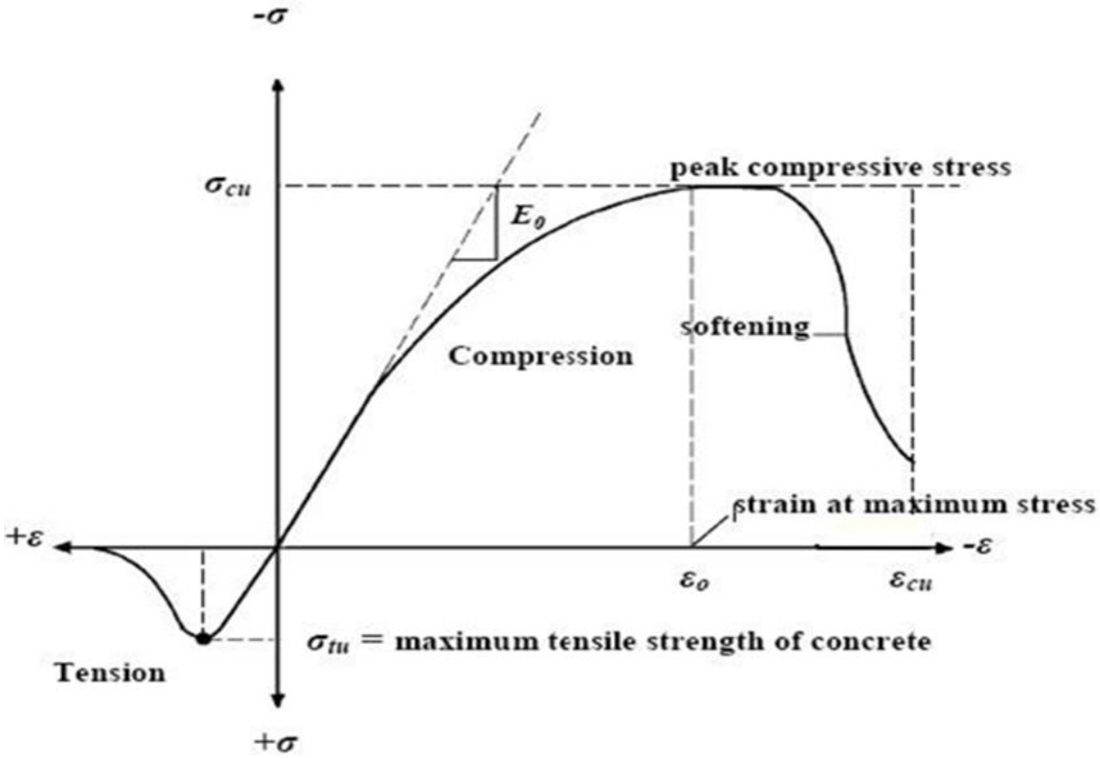


Figure 3.9: Typical uniaxial compressive and tensile stress-strain curve for concrete.

(Source: https://images.app.goo.gl/pnkxe5skBiNVnDfF7, Accessed 11 June,2022)

The present study assumed that the concrete is homogeneous and initially isotropic. The two main concrete failure mechanisms are cracking under tension and crushing under compression. The stress-strain relationship in compression for concrete used in ABAQUS is represented in Fig 3.10. A Poisson's ratio of 0.18 was used for concrete. The stress-strain follows a linear elastic relationship until the value of the failure stress is reached under Uni-axial tension. Stress-Strain curve used in ABAQUS as shown in material. Concrete damage plasticity (CDP) data are used in ABAQUS modeling.

Table 3.1: Material property of concrete

Modulus of elasticity, E (MPa)	15427.30
Poisson’s ratio	0.18
Characteristic compressive strength, f'_c (MPa)	20
Characteristic tensile strength(f_t), MPa	3

Table 3.2: Concrete damage plasticity parameter

Dilation Angle	31
Eccentricity	0.1
Fb0/fc0	1.16
k	0.67
Viscosity parameter	0.001

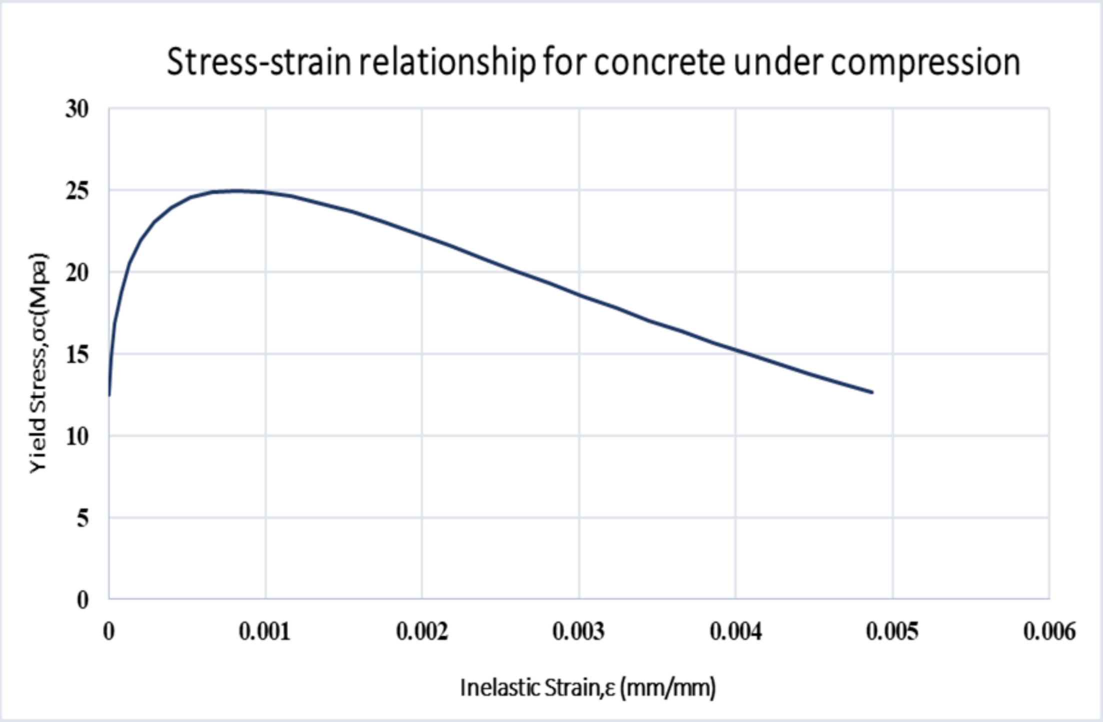


Figure 3.10: Stress-strain relationship for concrete under uniaxial compression.

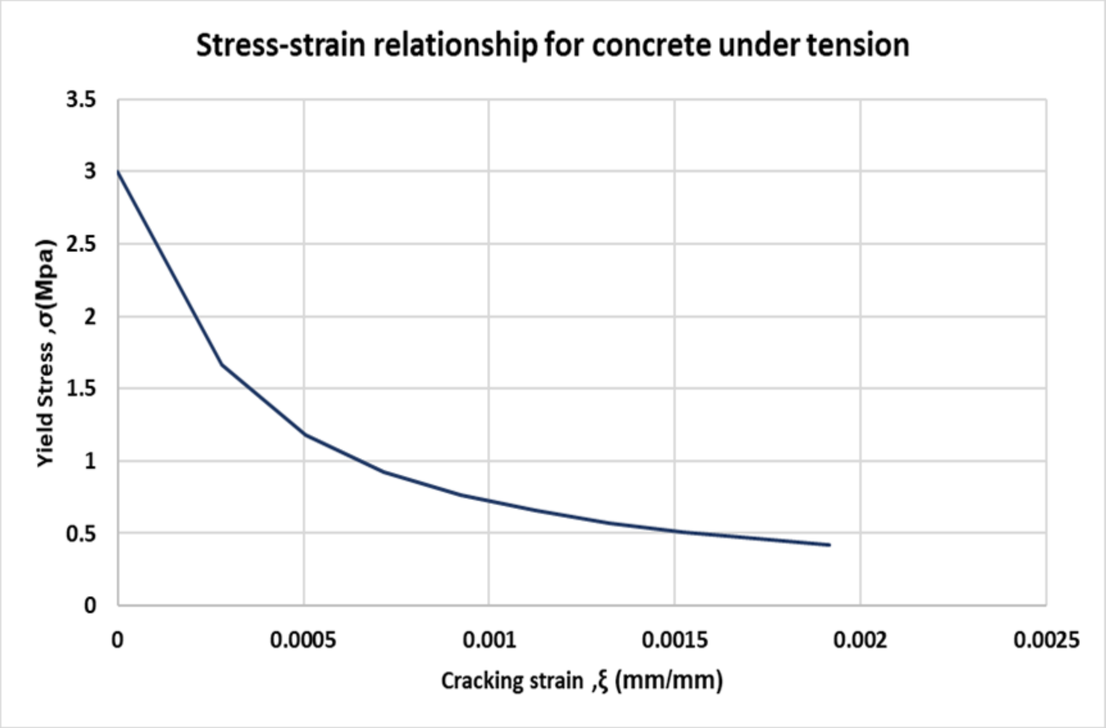


Figure 3.11: Stress–strain relationship for concrete under uni-axial tension.

3.5.2 Steel

Steel is assumed to be an elastic-perfectly plastic material and identical in tension and compression. Poisson's ratio of 0.3 was used for the steel reinforcement in this research.

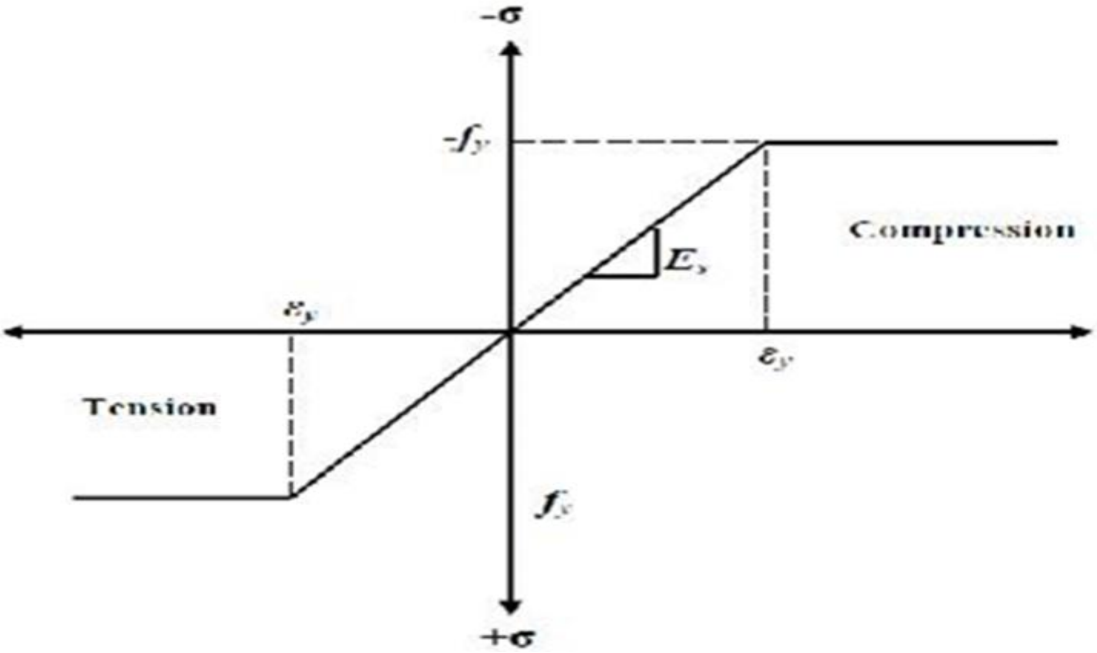


Figure 3.11: Stress-strain curve for steel reinforcement.

Table 3.3: Properties of reinforcing steel bars for main and cantilever beam

Elastic modulus E (GPa)	200
Nominal Diameter (mm)	12&10
Yield Stress (N/mm2)	420
Poisson's ratio	0.3
Tensile Strength (N/mm2)	655
Density tonne/mm^3	7.8e-8

Table 3.4: Properties of reinforcing steel bars for stirrups

Elastic modulus E (GPa)	200
Nominal Diameter (mm)	12&10
Yield Stress (N/mm2)	420
Poisson's ratio	0.3
Tensile Strength (N/mm2)	655
Density tonne/mm^3	7.8e-8

Figure 3.11: Stress-strain relationship for steel used in ABAQUS

3.5.3 Carbon Fiber Reinforced Polymer (CFRP)

FRP composites are materials that consist of two constituents. The constituents are combined at a macroscopic level and are not soluble in each other. One constituent is the reinforcement, in the form of fibers, i.e., carbon and glass, which is embedded in the second constituent, a continuous polymer called the matrix. Carbon and glass are typically stiffer and stronger than the matrix. The FRP composites are anisotropic materials, which means their properties are not the same in all directions. The material of CFRP is very light and strong as the tightly packed material is resistant to breaking due to its bonded structure. Deflections are reduced by using CFRP laminates to strengthen the RC slab with a large opening and thus the load-carrying capacity increases.

Table 3.5: Elastic and hasin damage properties of CFRP used in ABAQUS

Parameter	**Quantity**
Elastic modulus of fabric, E1, E2, respectively	130 and 8 GPa
Longitudinal and transverse Poisson's ratio	0.28
Shear modulus G12, G13, G23, respectively	4500, 4500, and 3600 Mpa
Longitudinal tensile and compressive strength, respectively	2200 and 2200 MPa
Transverse tensile and compressive strength, respectively	61 and 130 MPa
Longitudinal and transverse shear strength, respectively	85 and 40 MPa
Longitudinal tensile fracture energy	70 MJ/mm^2
Longitudinal compressive fracture energy	70 MJ/mm^2
Transverse tensile fracture energy	0.25 MJ/mm^2
Transverse Compressive fracture energy	0.25 MJ/mm^2

3.6 Model Development with ABAQUS

Based on the central objectives of this research, three-dimensional Finite Element models of reinforced concrete beam is developed. For developing a 3D finite element model in ABAQUS some modules have been followed. Which are:

- Element's type
- Material property
- Assigning sections

- Defining step
- Interaction between elements
- Specify boundary conditions and load
- Meshing
- Assigning job
- Evaluating the results

3.6.1 Creating and Assembling Parts

At first, in the Part module, Concrete was modeled using a 3D eight-node linear brick element (C3D8) with reduced integration and hourglass control. The C3D8 element is a general-purpose linear brick element, fully integrated (2x2x2 integration points). The shape functions can be found in. The node numbering follows the convention of Figure 3.13 and the integration points are numbered according to Figure 3.14. The solid element (C3D8) has eight nodes with three degrees of freedom at each node – translations in the nodal x, y, and z directions. The element is capable of plastic deformation, cracking in three orthogonal directions, and crushing.

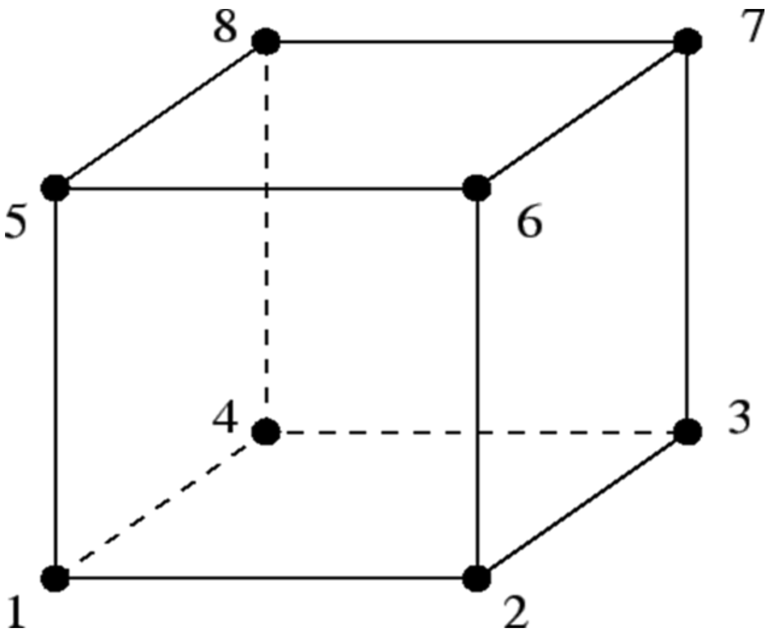


Figure 3.13: Node brick element

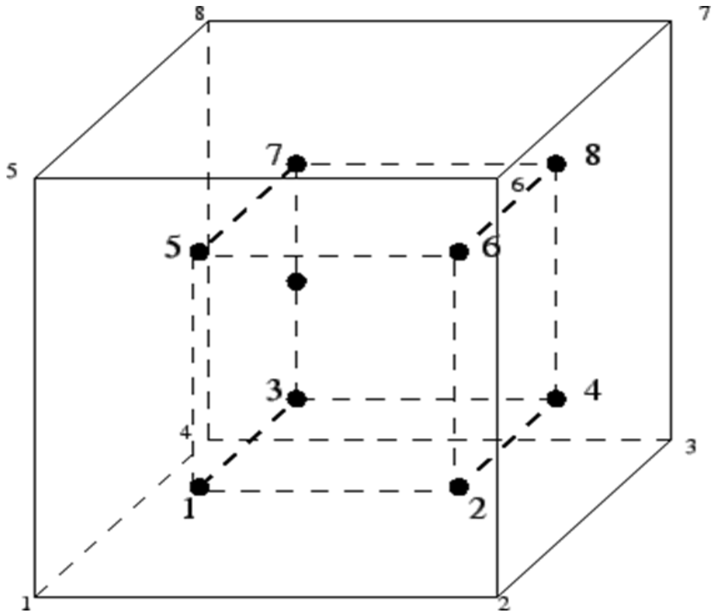


Figure 3.14: 2x2x2 integration point scheme in hexahedral elements

The embedded reinforcing steel bars were modeled using linear two-node truss elements (T2D3) with three degrees of freedom at each node. Truss element(T2D3) are used in two and three dimensions to model slender, line-like structures that support loading only along the axis or the centerline of the element. No moments or forces perpendicular to the centerline are supported.

Necessary partitions of the main concrete beam (of size 150 x230 x1500 mm) and cantilever beam (of size 150x230x400 mm) are made to facilitate load application and meshing. The steel reinforcement of size 1500 mm is modeled as two-node truss elements connected to the nodes of adjacent solid elements. Stirrups of size 100x180 mm are also designed with a two-node truss element. Linear 3D three-node triangular facet thin shell elements is used to model thevcomposites.

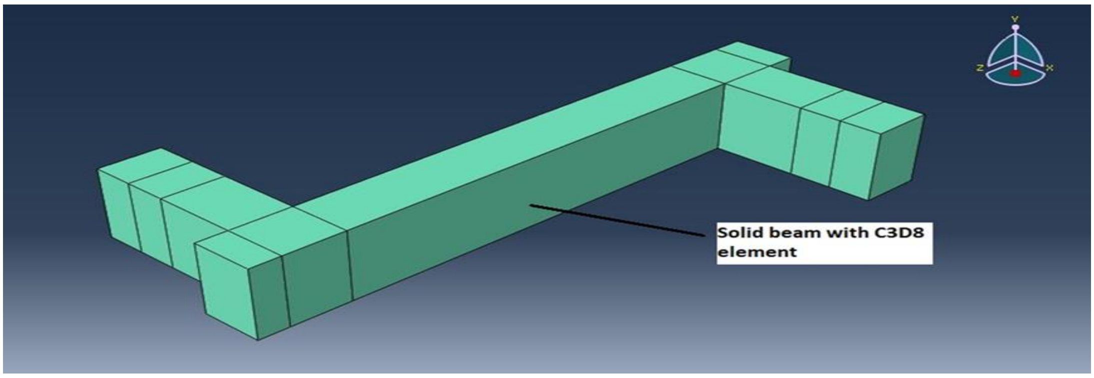


Figure 3.15: 3D-Solid beam designed in ABAQUS

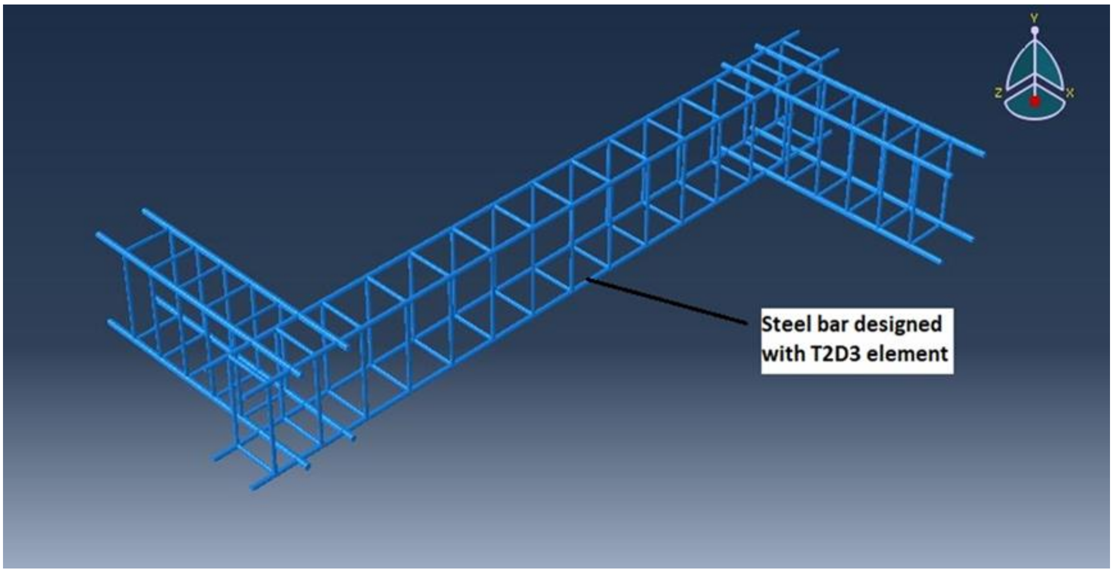


Figure 3.16: Reinforcement and Stirrups modelling

Eight initial plys are used to make a composite layer. For CFRP each layer is 0.145mm thick. For loading and Support 3D-Analytical rigid element is selected. Main facility of this rigid element is we don’t have to mash it.

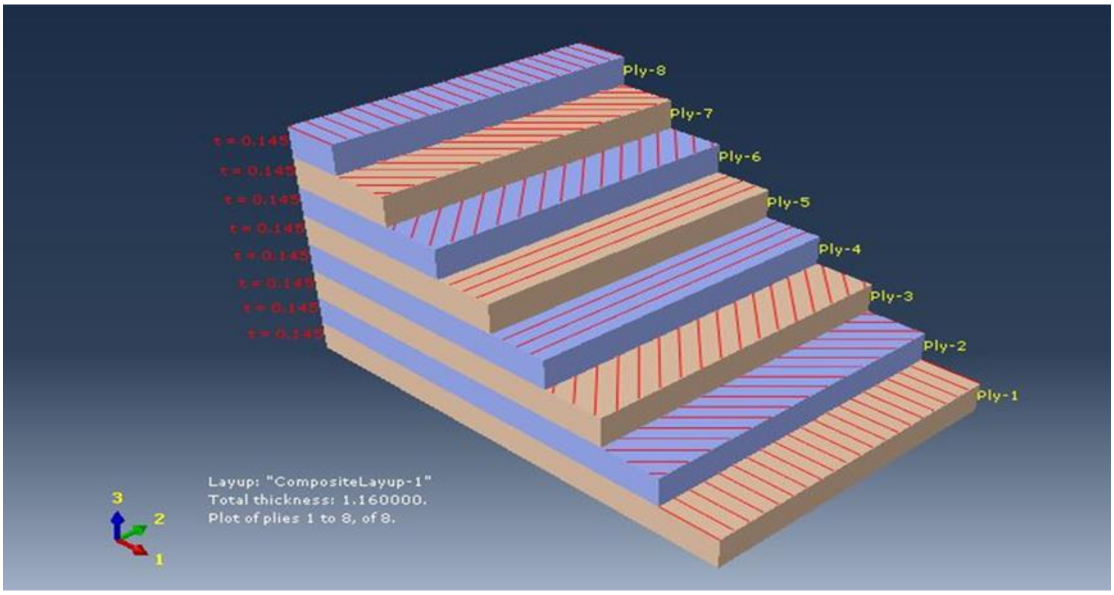


Figure 3.17: Composite ply layers orientation

In the property module, all the material properties are inputted and in the assembly module, all the parts are joined together. Embedded region constraint is used to make the bonding between the beam and reinforcement. Rigid body constraint is used to make a surface-surface contact between the beam and load-cells and supports. CFRP is assembled with a beam with Lamina type bonding. Some reference points are created to place the load for collecting output data.

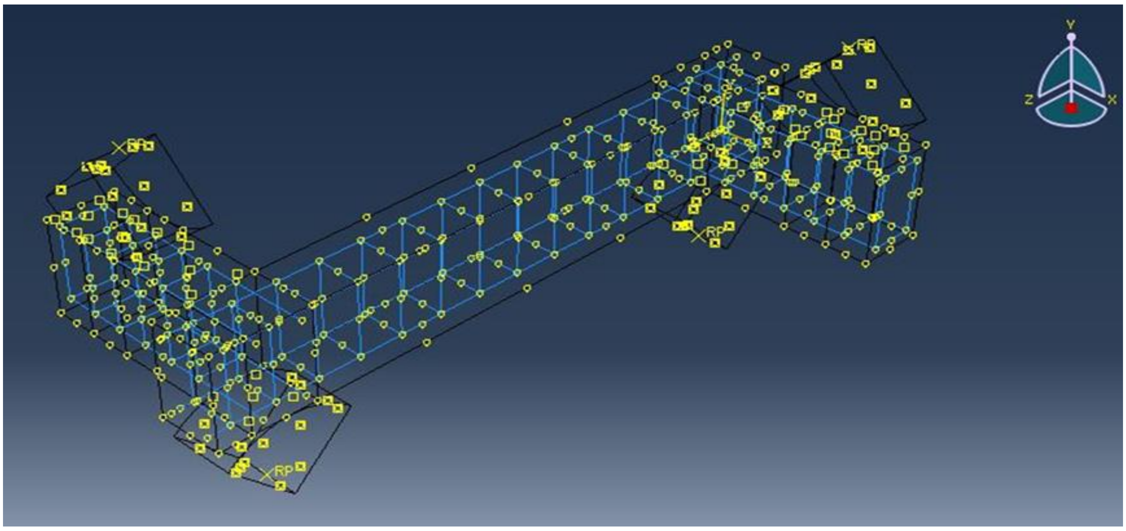


Figure 3.18: Constraint’s profile used in ABAQUS modeling

3.6.2 Mesh Sensitivity Test

Meshing is the process of generating nodes and elements. A mesh is generated by defining nodes and connecting them to define the elements. Meshing is one of the key components to obtaining accurate results from an FEA model. The elements in the mesh must take many aspects into account to be able to discretize stress gradients accurately. Typically, the smaller the mesh size, the more accurate the solution. After assembling and assigning the properties, a mesh sensitivity test has been done for finding the optimum mesh.

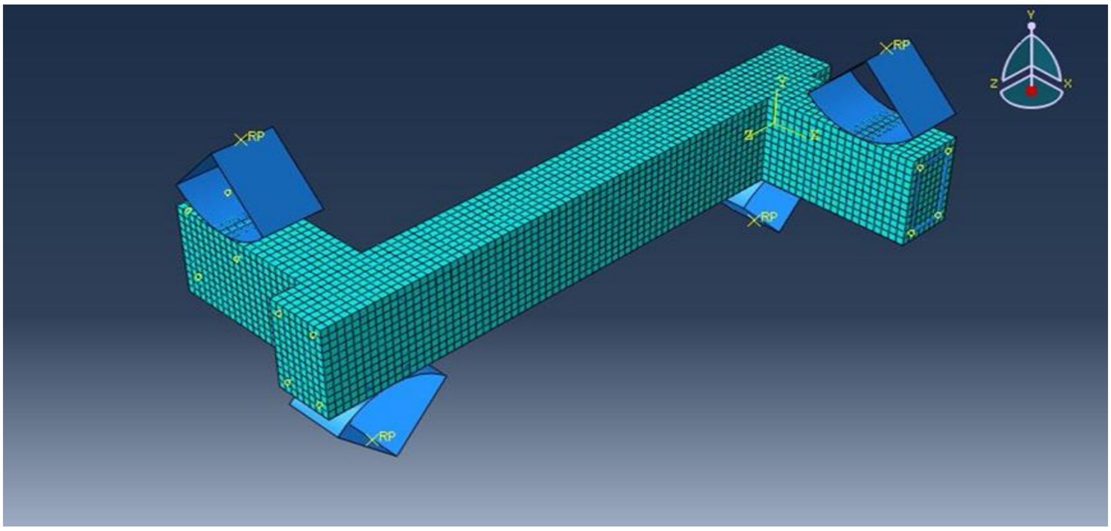


Figure 3.19: Meshed Beam

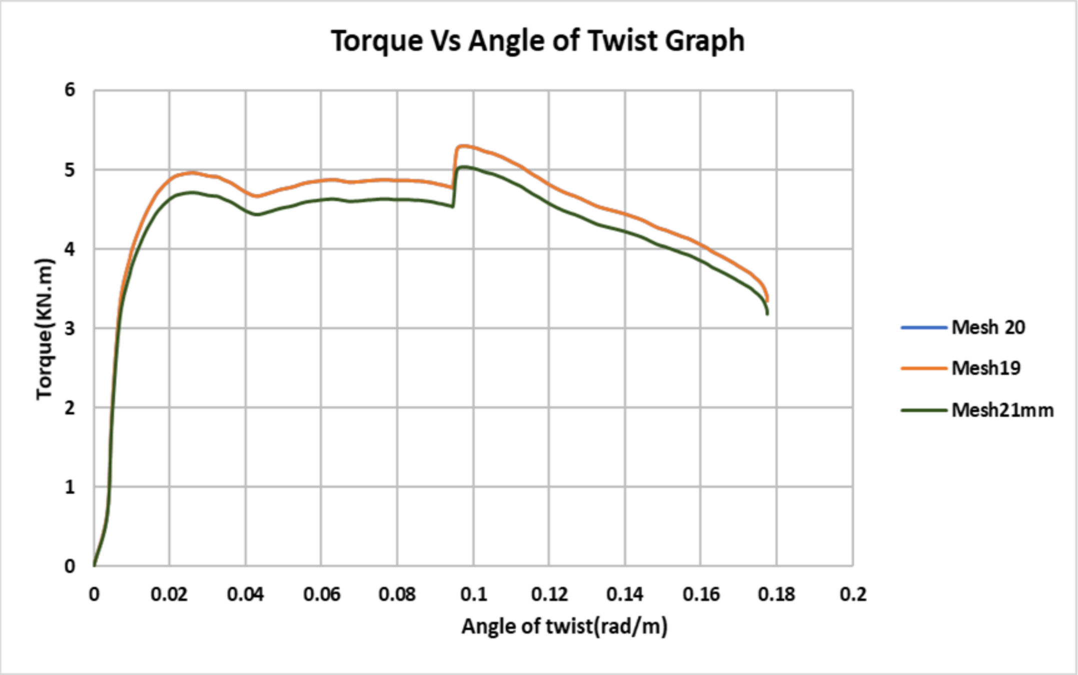


Figure 3.20: Torque vs Angle of Twist graph for finding optimum mesh.

From the Torque vs Angle of twist Graph, it is clear that 19mm and 20mm mesh gives a constant result, optimum mesh, 20 mm is selected for further analysis. CFRP is also modeled with optimum mesh Size. After meshing a job is created to perform the analysis.

3.6.3 Analytical Progress and Data Reading

The analysis has been carried out under displacement control. Two load-cell has been placed on the top of the cantilever beam and a constant displacement of 25mm has been applied at a rate of 1mm/min. This will create a pure torsional force at both ends of the beam and a Torque will be produced due to the cantilever part. Two hinge supports has been placed under the beam at a distance of 190mm from the two ends. These two hinges support will create a realistic Torque on the beam compared with practical life. A full Newton nonlinear analysis method has been conducted for each of the models. From the analysis total applied force is collected with respect to time. This force is multiplied with a lever arm to determine the applied torque in the beam.

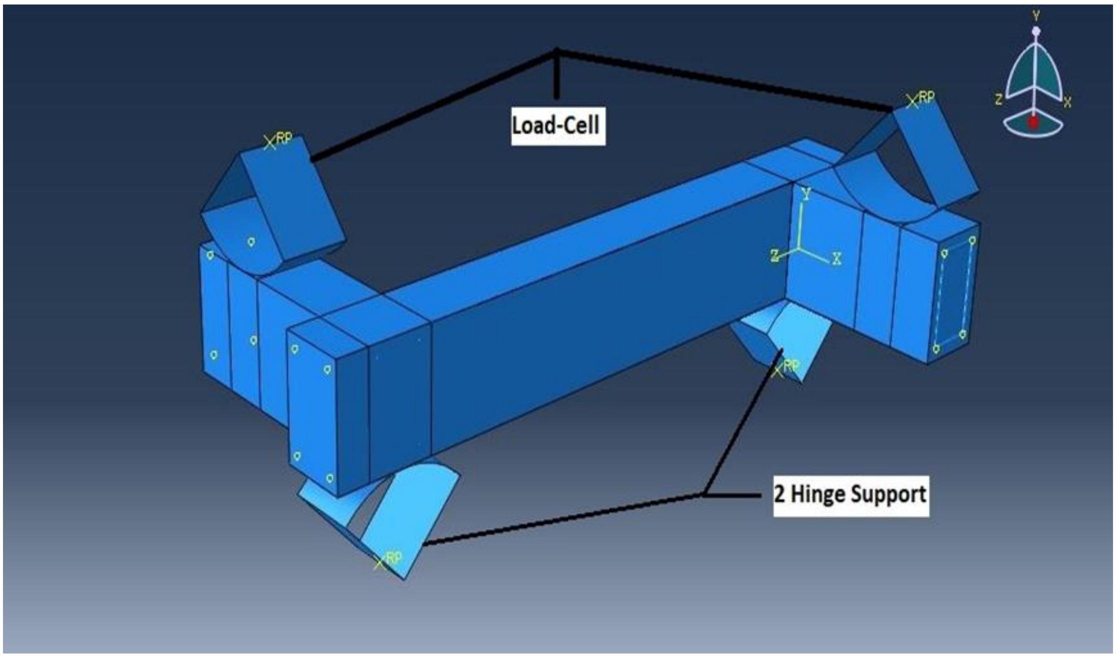


Figure 3.21: Final designed beam model in ABAQUS

Displacement with respect to time is recorded to find the angle of twist. The angle of twist is determined using this Equ,

$$Tan\theta = \frac{Down\ Reading}{200} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (3.1)$$

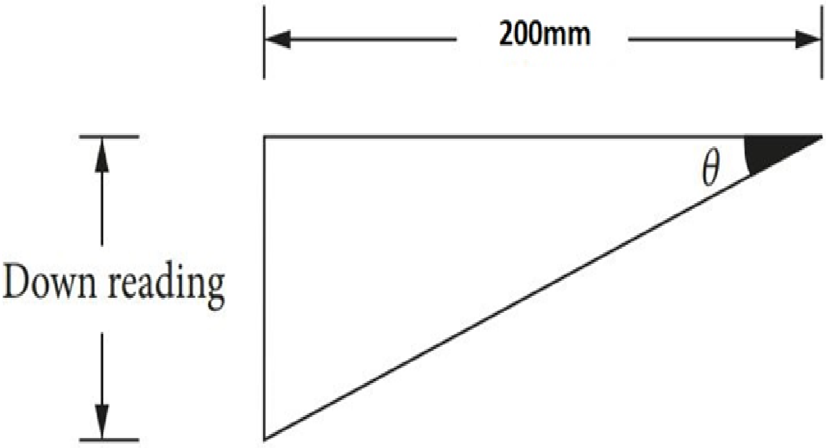


Figure 3.22: Angle of Twist measurement.

3.7 Modeled Beam Codes and Legends

The following beam codes and legends are used in this research paper:

Beam Code	**Legends**
Control Beam	CB
Fully CFRP wrapped beam	FCWB
45^0 Inclined CFRP wrapped strip beam	45CWSB
90^0 Vertical CFRP wrapped strip beam	90CWSB

CHAPTER 4

RESULTS AND DISCUSSION

4.1 General

This chapter includes numerical results of all beams with different types of configurations and orientation of CFRP. Their behavior throughout the test is described using recorded data on torsional behavior and the ultimate load-carrying capacity. The crack patterns and the mode of failure simulated by ABAQUS for each beam are also described in this chapter. All the beams are tested till complete failure. It is observed that the control beam had less torque resistance and high angle of twist values compared to that of the FRP strengthened beams.

Finally, the numerical result is verified with an experimental study.

4.2 Effect of CFRP on Increasing Torsional Strength

It is observed that introducing CFRP has increased the torque carrying capacity of the beam compared to the control beam. The angle of twist decreased compared to the control beam and load-carrying capacity also increased.

4.2.1 Control Beam Vs Fully CFRP Wrapped Beam

Table 4.1: Torque, Angle of Twist and Ultimate load data for control and Fully CFRP wrapped beam

Specimen	**Ultimate Torque (KN.m)**	**Increase in Torque %**	**Angle of Twist at Ult. Torque(rad/m)**	**Decrease in Angle of Twist (%)**	**Ultimate load(KN)**	**Increase in Ultimate load %**
CB	5.30		0.098		26.50	
FGWB	9.29	75.28	0.092	6.12	46.47	75.36

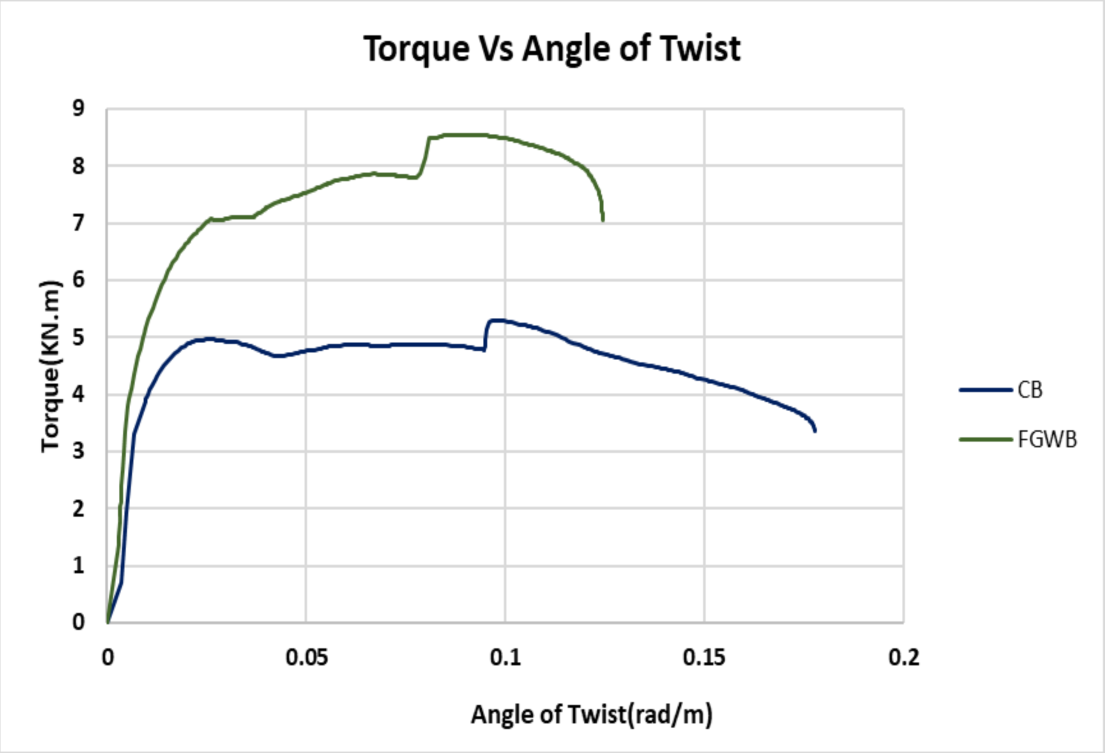


Figure 4.1: Torque vs Angle of twist graph between Control beam and Fully CFRP wrapped beam

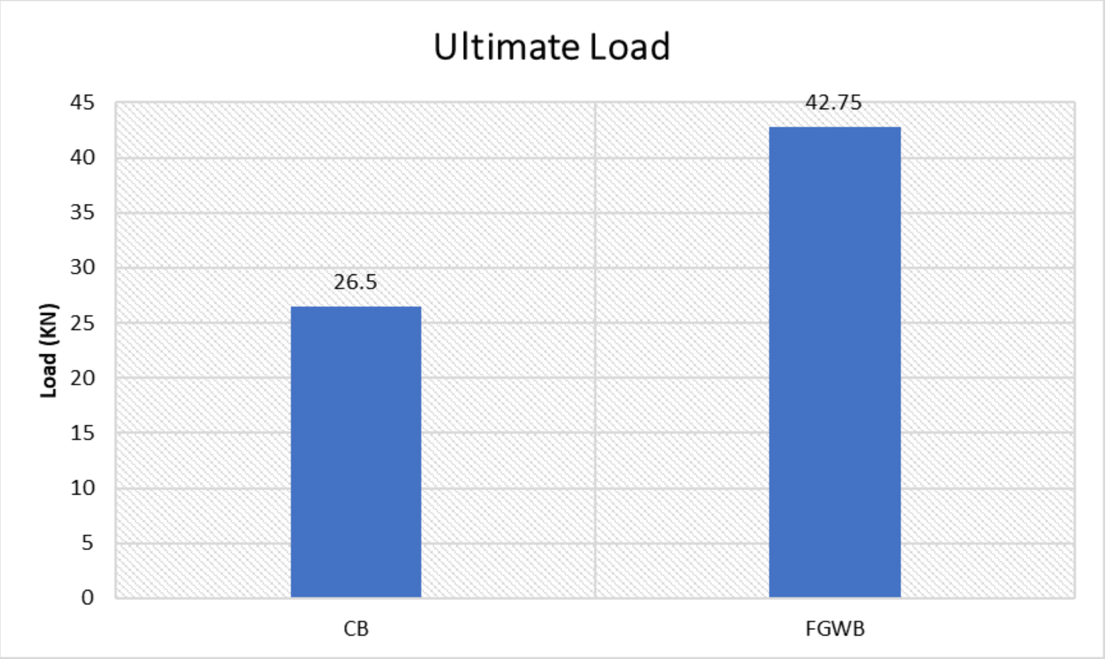


Figure 4.2: Ultimate load-carrying capacities of control and fully CFRP wrapped beam

4.2.2 Discussion

From the result, it is clear that FCWB has more torsional resistance than CB. Torsional resistance of FCWB has increased up-to 75.28% than CB and Angle of twist decrease up-to 6.12%. Ultimate load-carrying capacities increased up-to 75.36% than CB. From the torque and angle of twist graph, it is noticed that a linear increase of torque with the angle of twist for both CB and FCWB. For CB, after the yielding of the reinforcement an ultimate peak value of torque is noticed and after that ultimate failure of the beam occurs. But for FCWB after the linear increase of torque instead of yielding reinforcement CFRP start carrying torque and a high increase of graph is seen. CFRP also increases the stiffness of the beam.

4.2.3 Control Beam Vs 45° Inclined CFRP Wrapped Strip Beam

Table 4.2: Torque, Angle of Twist and Ultimate load data for control and 45° Inclined CFRP Wrapped Strip Beam

Specimen	**Ultimate Torque (KN.m)**	**Increase in Torque %**	**Angle of Twist at Ult. Torque(rad/m)**	**Decrease in Angle of Twist (%)**	**Ultimate load(KN)**	**Increase in Ultimate load %**
CB	5.30		0.098		26.50	
45CWSB	6.55	23.85	0.066	32.65	32.75	23.58

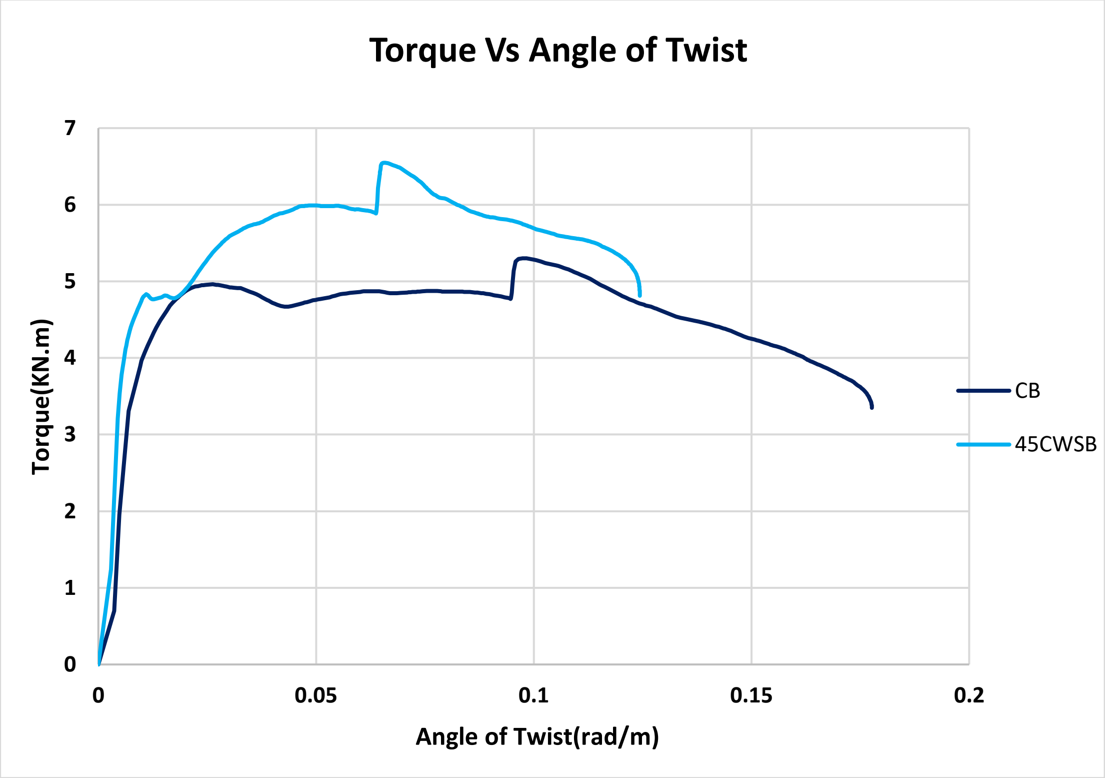


Figure 4.3: Torque vs Angle of twist graph between Control beam and 45° inclined CFRP wrapped strip beam

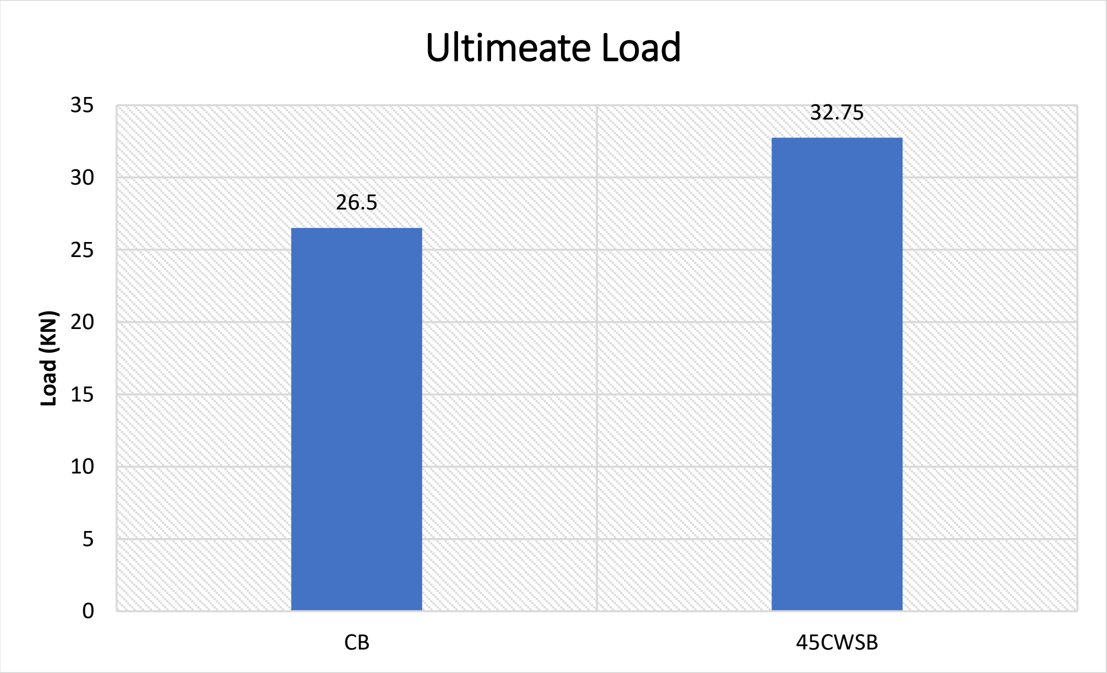


Figure 4.4: Ultimate load-carrying capacities of control and 45^0 inclined CFRP wrapped strip beam

4.2.4 Discussion

From the result, it is clear that 45CWSB has more torsional resistance than CB. Torsional resistance of 45CWSB has increased up-to 23.58% than CB and Angle of twist decreased up-to 32.65%. Ultimate load-carrying capacities increased up-to 23.58% than CB. From the torque and angle of twist graph, it is noticed that a linear increase of torque with the angle of twist for both CB and 45CWSB. For CB, after the yielding of the reinforcement an ultimate peak value of torque is noticed and after that ultimate failure of the beam occurs. But for 45CWSB after the linear increase of torque instead of yielding reinforcement CFRP start carrying torque and a high increase of graph is seen. CFRP also increases the stiffness of the beam.

4.2.5 Control Beam Vs 90° Vertical CFRP Wrapped Strip Beam

Table 4.3: Torque, Angle of Twist and Ultimate load data for control and 90°vertical CFRP wrapped strip beam

Specimen	**Ultimate Torque (KN.m)**	**Increase in Torque %**	**Angle of Twist at Ult. Torque(rad/m)**	**Decrease in Angle of Twist (%)**	**Ultimate load(KN)**	**Increase in Ultimate load %**
CB	5.30		0.098		26.50	
90CWSB	5.49	3.58	0.033	66.33	27.45	3.58

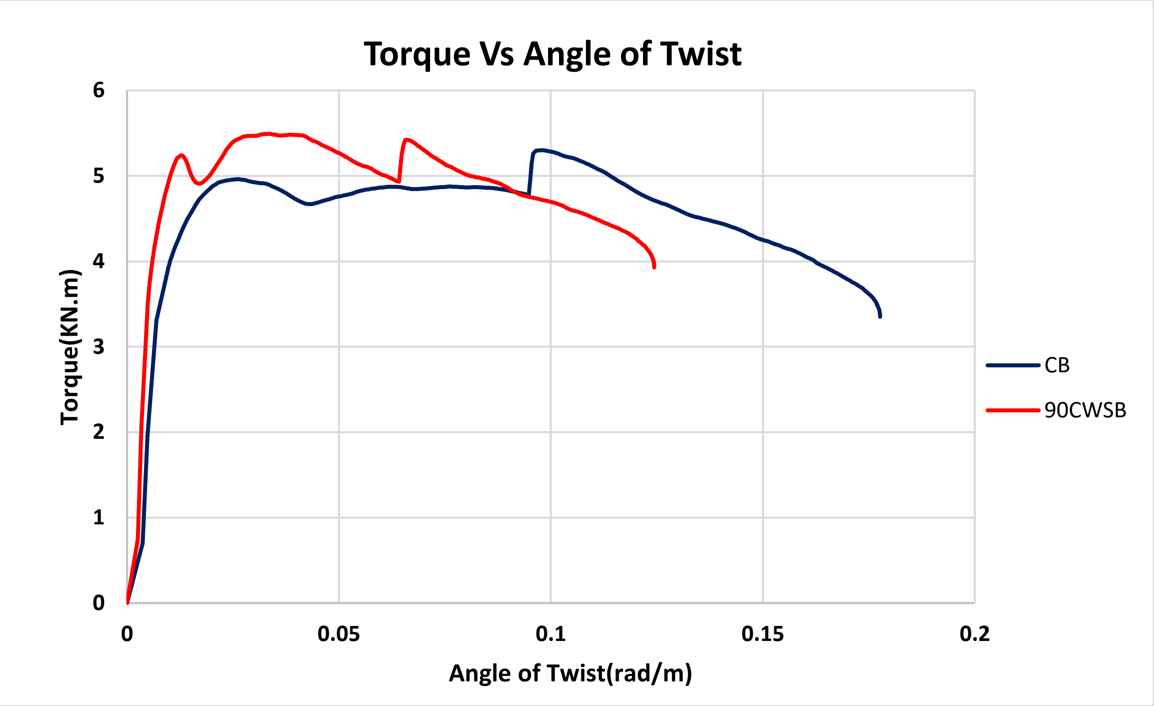


Figure 4.5: Torque vs Angle of twist graph between Control beam and 900 vertical

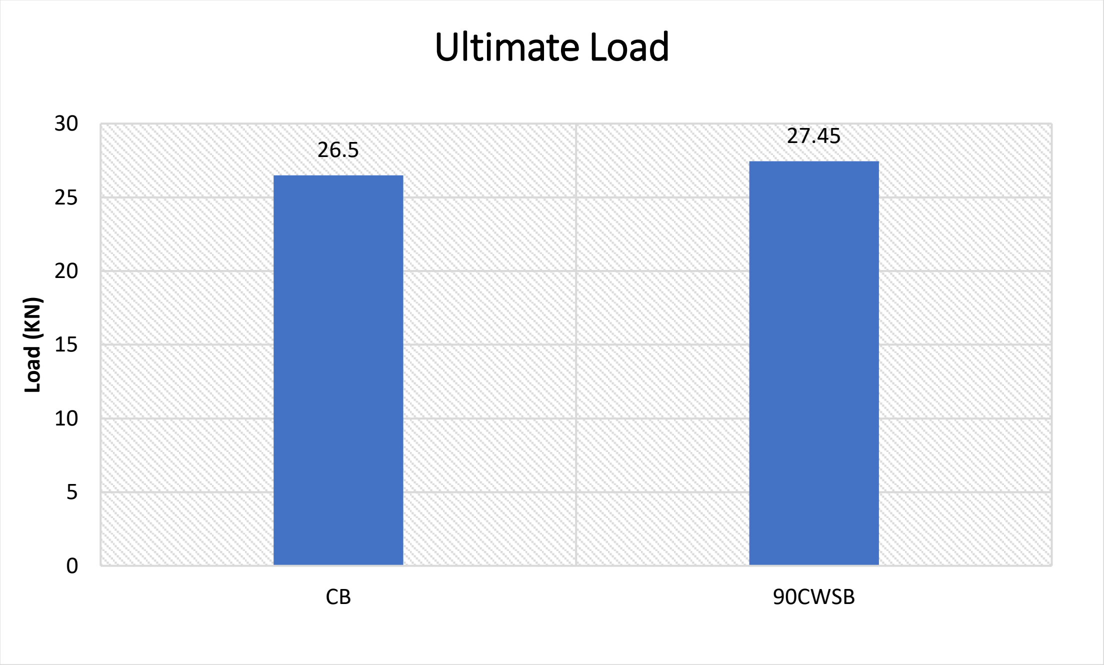


Figure 4.6: Ultimate load carrying capacities of control and 90° vertical CFRP wrapped strip beam.

4.2.6 Discussion

From the result, it is clear that 90CWSB has more torsional resistance than CB. Torsional resistance of 90CWSB has increased up-to 3.58% than CB and Angle of twist decreased up-to 66.33%. Ultimate load-carrying capacities increased up-to 3.58% than CB. From the torque and angle of twist graph, it is noticed that a linear increase of torque with the angle of twist for both CB and 90CWSB. For CB, after the yielding of the reinforcement an ultimate peak value of torque is noticed and after that ultimate failure of the beam occurs. But for 90CWSB after the linear increase of torque instead of yielding reinforcement CFRP start carrying torque and an increase of graph is seen. CFRP also increases the stiffness of the beam.

4.2.7 Summary

Table 4.4: Summary table of Torque, Angle of Twist and Ultimate load data for control and 90° vertical CFRP wrapped strip beam

Specimen	**Ultimate Torque (KN.m)**	**Increase in Torque %**	**Angle of Twist at Ult. Torque(rad/m)**	**Decrease in Angle of Twist(%)**	**Ultimate load(KN)**	**Increase in Ultimate load %**
CB	5.30		0.098		26.50	
FCWB	9.29	75.28	0.092	6.12	46.47	75.36
45CWSB	6.55	23.85	0.066	32.65	32.75	23.58
90CWSB	5.49	3.58	0.033	66.33	27.45	3.58

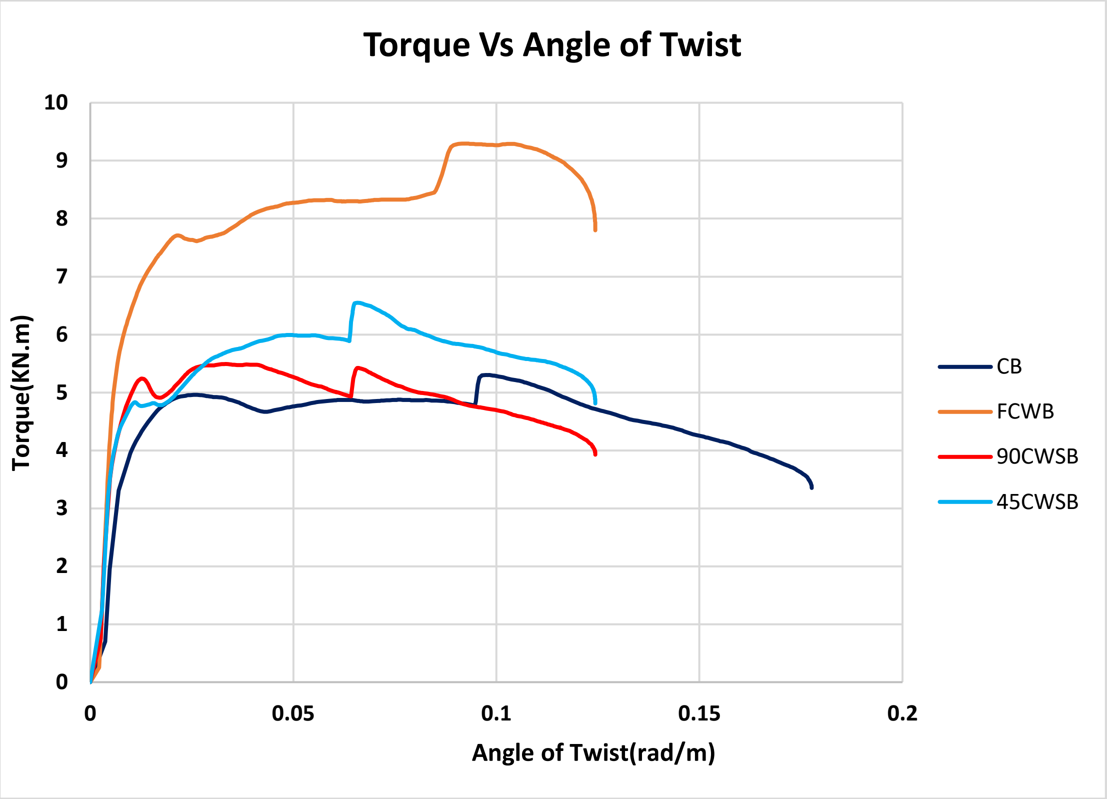


Figure 4.7: Torque vs angle of twist graph of all types of beams

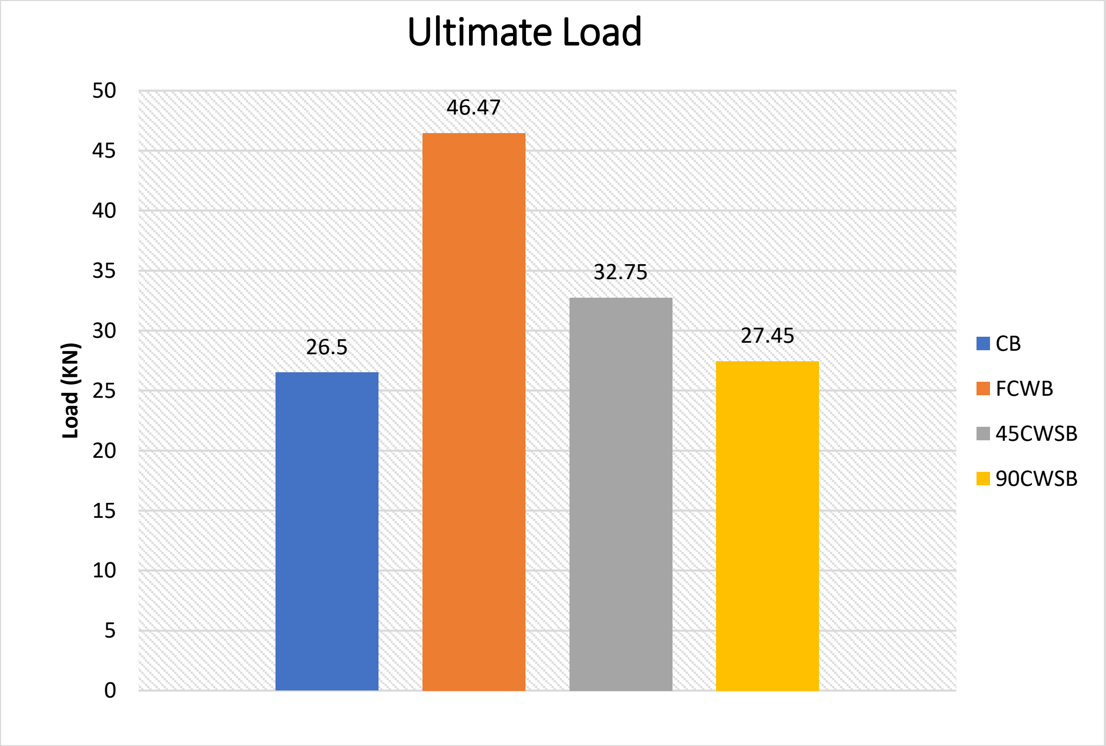


Figure 4.8: Ultimate load of all beams

4.2.8 Discussion

From the summary table, it is clear that obviously FRP composites increased the torsional strength and decreased the Angle of twist of the normal RC beam. CFRP increased torsional resistance 75.28 %. Again, CFRP Decreased the Angle of a twist by 66.33%. But CFRP Also Increased the Stiffness of the beam. This makes the beam more brittle than a normal RC beam. Ductility index reduced.

In this study 3 different types of the orientation of CFRP composite have been used. Which are: Fully CFRP wrapped, 45^0 Inclined CFRP wrapped strip and 90^0 Vertical CFRP wrapped strip. Among of them Fully CFRP wrapped beam showed a good result to increase the torsional resistance, but this orientation is not good for decreasing the angle of twist.

On the other side, 90^0 Vertical CFRP wrapped strip beam showed the excellent performance to decrease the angle of twist, but they performed too poor to resist the upcoming toque.

45^0 Inclined CFRP wrapped strip beam performed average between Fully CFRP wrapped and 90^0 Vertical CFRP wrapped strip beam. 45^0 Inclined CFRP increased torsional resistance significantly but not good as fully CFRP wrapped beam as well as decrease the angle of twist decently but not good as 90^0 Vertical CFRP wrapped strip beam.

4.3 Crack and Failure Pattern

The ABAQUS program records a crack pattern at each applied load step. A cracking sign represented by a block appears when principal tensile stress exceeds the ultimate tensile strength of the concrete. The cracking sign appears perpendicular to the direction of the principal stress. ABAQUS program displays blocks at locations of cracking or crushing in concrete elements. It shows the appearance of flexural cracks, diagonal Torsional cracks, and compression cracks. Generally, torsional cracks create 45^0 in the shear plane and torsional cracks are on both sides but in reserve direction. Pure torsion in a beam is typified by a series of inclined cracks running roughly parallel throughout the length of the member. The cracks basically form a spiral, running up one face of the beam, across the top, down the other side, and back across the bottom to connect with another crack on the first face.

If only an isolated portion of the beam is accessible, a torsion crack may appear similar to a shear crack. However, in torsion, the crack on the far face will be at the opposite angle to that on the front face while in shear the cracks on both faces will be at the same angle.

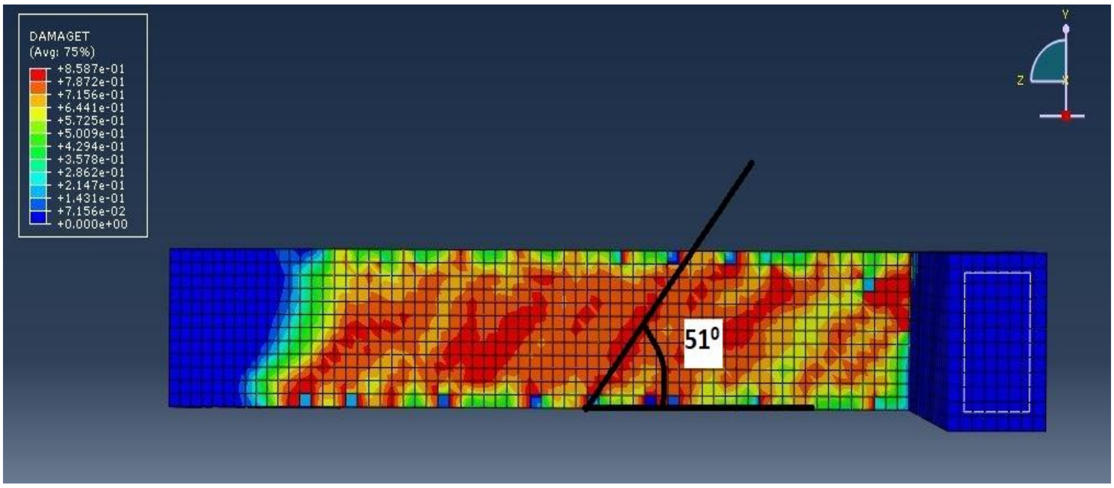


Figure 4.9: Torsional Crack on 1st face of CB

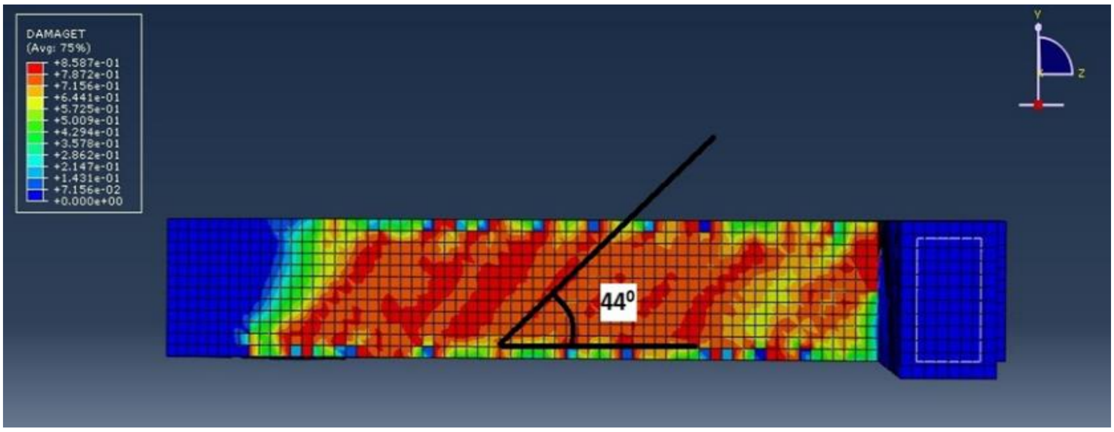


Figure 4.10: Torsional Crack on 2^{nd} face of CB

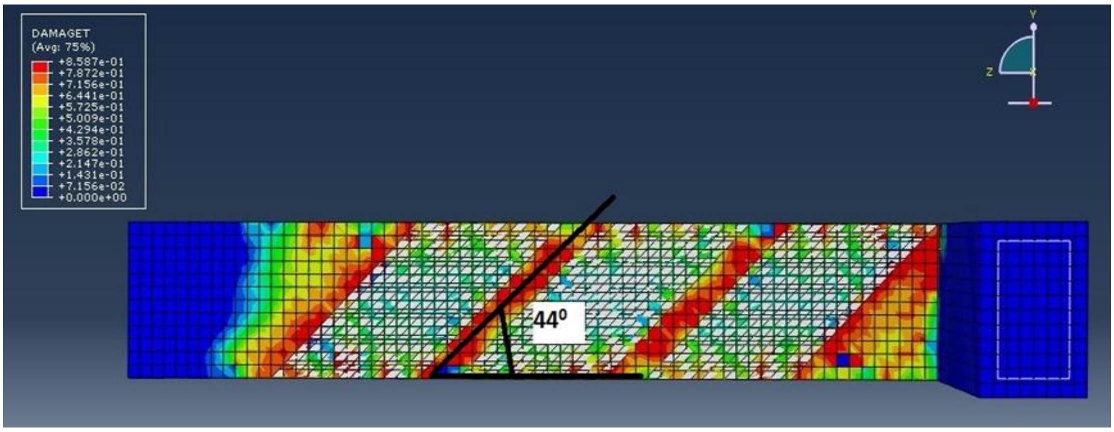


Figure 4.11: Torsional Crack on 1^{st} face of 45FWSB

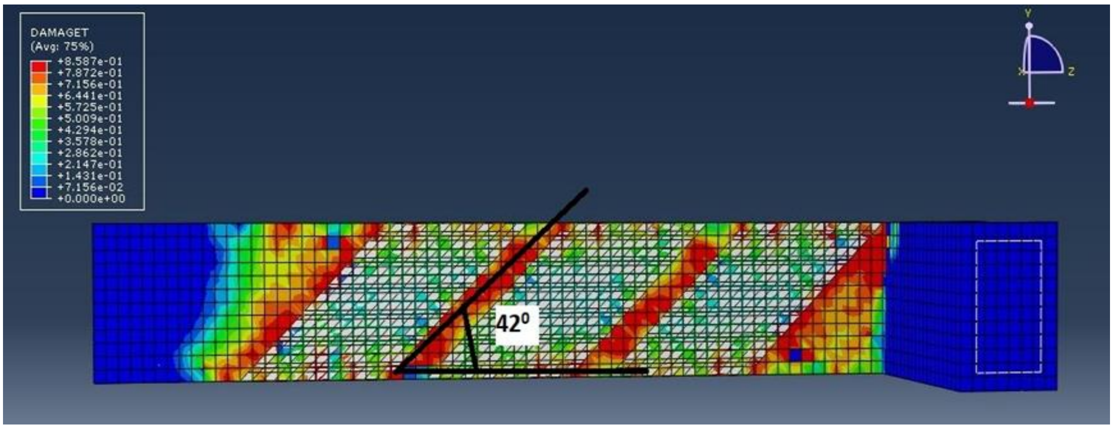


Figure 4.12: Torsional Crack on 2nd face of 45FWSB

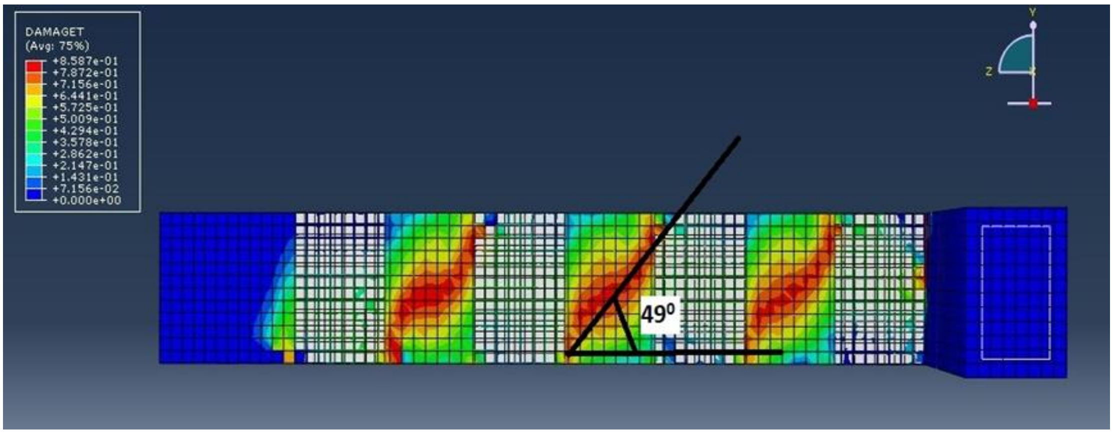


Figure 4.13: Torsional Crack on 1st face of 90FWSB

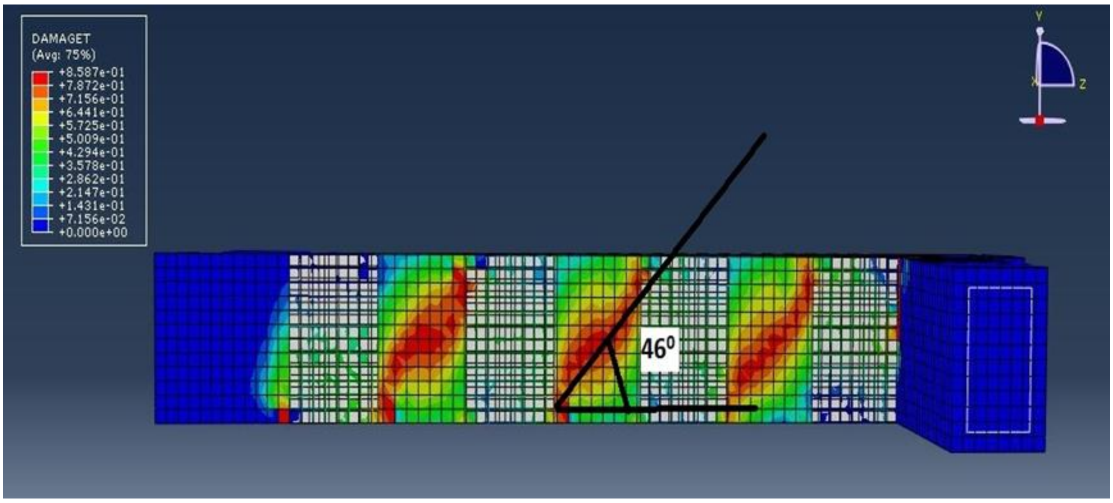


Figure 4.14: Torsional Crack on 2nd face of 90FWSB

4.4 Discussion

After inspecting all the cracks, it is seen that all the cracks create $(42\text{-}50)^0$ angle with respect to principal stress direction. This clearly indicated that these cracks are torsional cracks. This also helped to validate the finite element model.

4.5 Validation of FEM

Many parameters in a finite element analysis are uncertain. This will inevitably account for some differences in the behavior of the real structure and results of the analysis. Validation of finite element model is an important criterion to make to model more acceptable.

(Kumar et al., 2017) experimented this same setup which is analyzed in this Study but they used steel fiber reinforced concrete (SFRP) to increase the torsional resistance but in this research CFRP and GFRP are used. Though Control beam is same for all. From the experiment they have found out that normal reinforced concrete can resist up-to 6.43 KN.m torque and from the FE analysis it is seen that CB take up-to 5.30 kN.m torque.

Table 4.5: Error percentage between Experimental and FE analyzed beam

Program	**Ultimate Torque(kN.m)**	**Error (%)**
Experiment Beam	6.43	
FE analyzed Beam	5.30	17.57

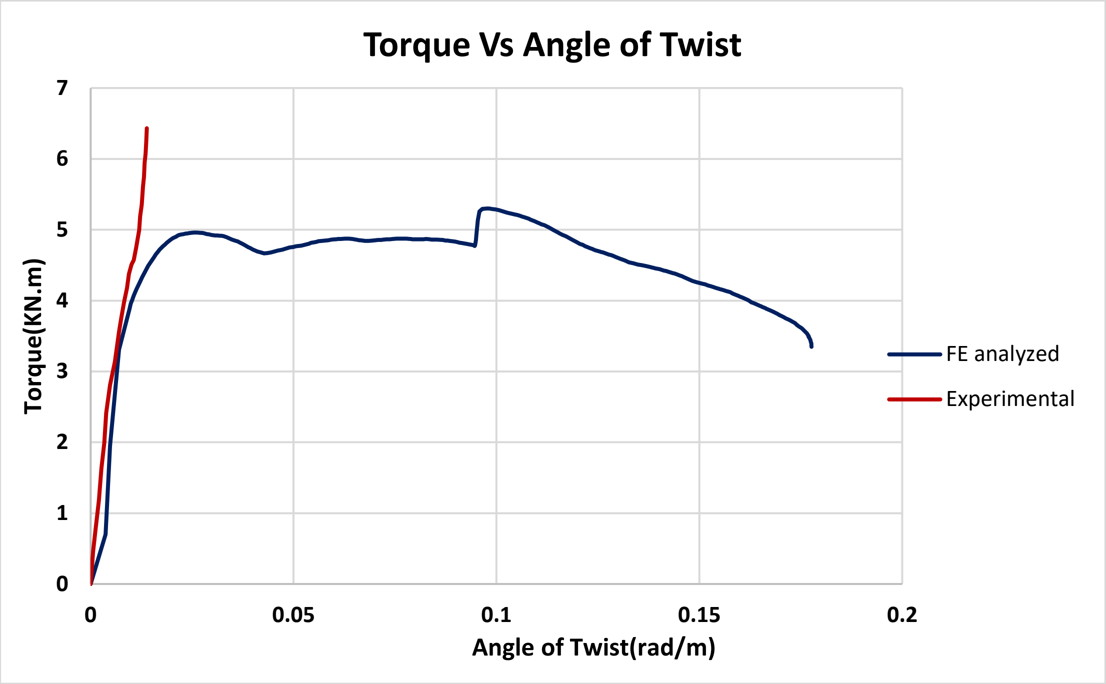


Figure 4.15: Torque vs Angle of Twist of Exp and CB

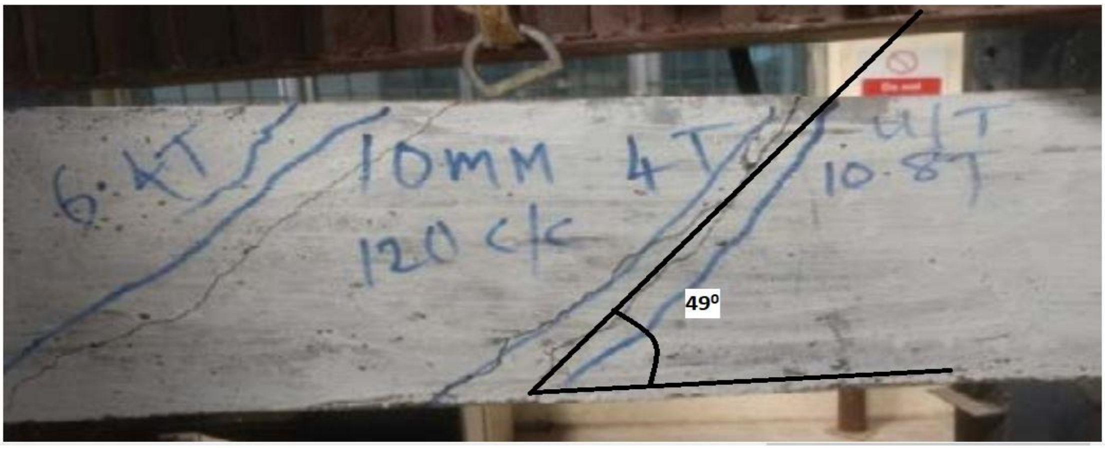


Figure 4.16: Experimental crack pattern

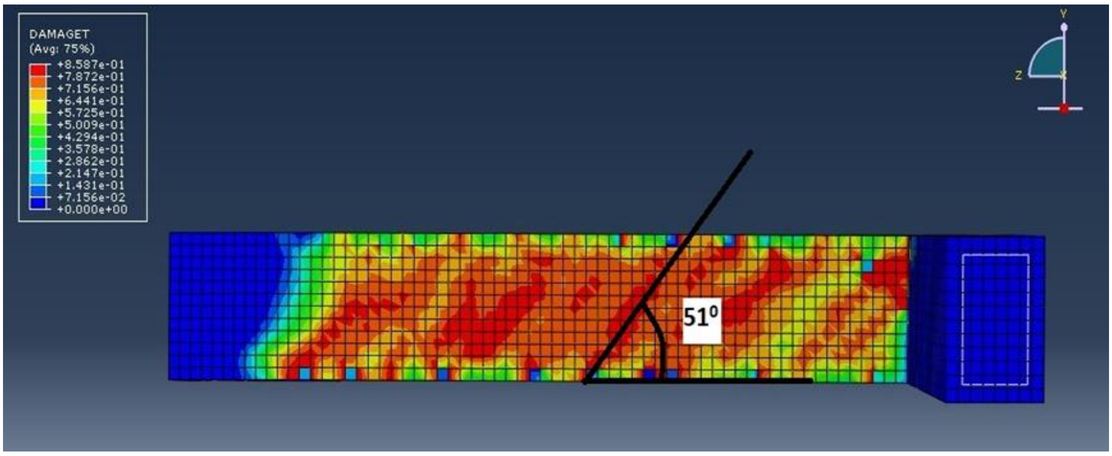


Figure 4.17: FE model crack pattern

The crack and failure pattern of the FE model also matches with the Experimental beam. This is also a validation of the FE model.

4.6 Comparison of FE Results Using Formula available in Literature

Analytical analysis has been conducted to determine the ultimate torque and cracking angle of the Control beam, as well as FRP, strengthened beam. This finding is compared with the FE model result. The full torsional strength of CFRP-strengthened RC beams can be analyzed by the design codes using the principle of superposition from both the CFRP and steel reinforcement. The analytical analysis will make the model more valid and reasonable.

4.6.1 Analytical Calculation

The softened space truss theory is a well-known analytical model for the problem of torsion in RC beams with bars and stirrups. The space truss analysis assumes that the external torsional moment T is resisted by an internal torque resulting from the shear flow q, which is developed in the center of a shear flow zone with an effective wall thickness td.

The ultimate torsional strength for the FRP-strengthened tested beams, Tu, can be achieved by adding the contribution due to fibers and due to reinforced concrete beam, as follows:

$$\text{Tu}=\text{Tu (RC)} +\text{Tu (FRP)} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots.. (4.1)$$

Where Tu denotes the nominal torsional capacity of the FRP strengthened beam. Tu,(RC) is calculated as in equations (5.2) according to the recommendations of ACI [318-14]:

$$\text{Tu(RC)} = \frac{2(0.85)\text{Ao} * \text{At} * \text{fyv}}{\text{S}} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (4.2)$$

Where, A_o= the shear flow area according to ACI 318-14, mm^2

A_t= Area of the transversal steel reinforcement (stirrups), mm^2

F_{yv}= Yield stress of transversal steel reinforcement, MPa

S= Spacing of steel stirrups, mm

The cracking angle can be calculated with the (4.3) equation.

$$\tan\theta = \sqrt{\frac{Ast * fst * Po}{Asl * fsl * S}} \ldots\ldots\ldots\ldots\ldots\ldots\ldots..(4.3)$$

Where,

A_{st}=Area of one-legged steel stirrup, mm2

A_{sl}=Total area of steel longitudinal bars,(mm2)

P_o=Perimeter of the centerline of shear flow,(mm)

f_{sl},f_{st}= stresses of the longitudinal and transverse reinforcement,(MPA)

S= spacing of steel stirrups,(mm)

FIB Bulletin-14, 2001 design model states that an externally bonded FRP laminate will grant contribution to the torsional capacity only if full wrapping around the beam's cross-section is applied, so that the tensile forces carried by the FRP on each side of the cross-section may create a continuous loop. The technical document also provides for the possibility of using inclined FRP strips as a strengthening solution. Based on the assumption of the validity of the truss mechanism, the following equations (4.4), (4.5), and (6.6) are provided to predict the FRP contribution to strength Tu,(FRP):

$$TU,(FRP) = 2\varepsilon fk,eEfu\frac{tf}{Sf}bh.cot\theta \ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(4.4)}$$

$$\varepsilon fk,e = 0.8\varepsilon fe \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(4.5)}$$

$$\varepsilon fe = 0.17\left(\frac{fc'^{\frac{2}{3}}}{Efu\rho f}\right)^{03}\varepsilon fu \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots.. \text{(4.6)}$$

Where,

B_{xh} = Cross section dimensions of beam

E_{fu} = Modulus of elasticity of FRP at ultimate

f'_c = Concrete compressive strength, (MPA)

t_f= Thickness of fiber laminate, mm

b_f = Width of the CFRP strips, mm

S_f = Centre-to-center spacing of FRP strips, mm

ε_{fe} = Effective FRP strain, mm/mm

ρ_f can be calculated using equation (4.7),

$$\rho f = \frac{nf*tfd*bf*Pf}{Ac*sf} \qquad \text{……………………………..(4.7)}$$

Where,

n_f = Number of plies of FRP sheets

A_c = cross-sectional area of the beam

P_f = Perimeter of the strengthened beam cross-section using FRP, mm

t_{fd}= Fabric design thickness, mm

Table 4.6: Used parameter values used in this study for calculating Tu(cal)

Used parameters	**Values**
A_o= the shear flow area	18000 mm2
A_t= Area of the transversal steel reinforcement	50.267 mm
F_{yv}= Yield stress of transversal steel reinforcement	280 MPa
S= Spacing of steel stirrups	100 mm
A_{sl}=Total area of steel longitudinal bars	314.16
P_o=Perimeter of the centerline of shear flow	560 mm
f_{sl},f_{st}= stresses of the longitudinal and transverse reinforcement	656 MPa, 370 MPa
B_{xh} = Cross section dimensions of beam	150x230 mm
E_{fu} = Modulus of elasticity of FRP at ultimate	130000,55000 MPa
f'_c = Concrete compressive strength	20 MPa
b_f = Width of the CFRP strips	610 mm
S_f = Centre-to-center spacing of FRP strips	300mm,150mm,50mm
ε_{fe} = Effective FRP strain	0.017 mm/mm
n_f = Number of plies of FRP sheets	8
A_c = cross sectional area of beam	150x230 mm
P_f = Perimeter of the strengthened beam cross section using FRP	560 mm
t_{fd}= Fabric design thickness	0.145 mm

Table 4.7: Comparison between Calculated T_u and Analyzed T_u with FEM

Specimen	**T_u,(RC)(KN.m)**	**T_u,(FRP)(KN.m)**	**T_u(Cal)(kN.m)**	**T_u(FEM)(KN.m)**	$\frac{\boldsymbol{Tu(FEM}}{\boldsymbol{Tu(Cal)}}$
CB	4.35		4.35	5.30	1.20
FCWB	4.35	4.87	9.22	9.29	1.007
45CWSB	4.35	2.26	6.61	6.55	0.990
90CWSB	4.35	1.11	5.46	5.49	1.005

4.6.2 Discussion

From table 4.10 it is seen that the error percentage between analytical calculation and FE result varies from 0.5 to 21%. Many researchers have confirmed that a 20% error in results between FE analysis and analytical calculation is acceptable. According to this, the FE analysis conducted through this study is acceptable.

CHAPTER 5

CONCLUSIONS AND FUTURE WORKS

5.1 Conclusions

After completing all the Finite element analysis result has been extracted from the software. All the Torque vs Angle of twist graph has been plotted. All the FRP wrapped beam graphs are compared with the Control beam graph and significant improvement has been noticed. The ultimate load-carrying capacities of all the beams are also determined. Based on the finite element result and experimental work and analytical calculation following conclusion are drawn:

- The cracking and ultimate torque of all strengthen beams were greater than those of the control beams.
- The increase in magnitude depends on the FRP strengthening configurations.
- The maximum increase in torque is obtained for fully CFRP wrapped configurations.
- Fully CFRP wrapped beam increased torsional resistance up-to 75.28 % than control beam.
- 90^0 Vertical CFRP wrapped strip beam decrease the maximum amount of angle of twist which is 66.33%
- Fully wrapped orientation increases the torque maximum but in case of decreasing angle of twist, this orientation is not suitable.
- 90^0 Vertical FRP orientation decreases the angle of twist maximum but in case of increasing torque; this orientation is not recommendable.
- 45^0 Inclined FRP orientation increased the torque resistance as well as decreased the angle of twist.
- The maximum increase in torque by 45^0 Inclined FRP orientation is 23.85% and the maximum decrease in angle of twist is 32.65%
- From the crack patterns, it is seen that all cracks are between 42-50 degrees.
- Compared to the Experimental work conducted by (Kumar et al., 2017) and FE analyzed result, the error is only 17.57%.
- Compared to the FE analyzed result and analytical calculation, it is seen that error varies from 0-20%.

5.2 Limitations and Recommendations for Future Works

In this study, only the Abaqus 6.14 software is used for the analysis. The software was a trial version; original software will be gives the more accurate results.

The following working scopes can be researched in the future:

- To Increase the torsional strength of RC beam using Steel fiber reinforced concrete (SFRP).
- To increase the torsional strength of RC beam using CFRP and GFRP experimentally.
- To Increase the torsional strength of RC beam using Jute fiber.
- To Increase the torsional strength of RC beam Recycled material.
- To Increase of flexural strength of RC beam using CFRP and GFRP Composites.

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