NUMERICAL ANALYSIS OF RECTUNGALER RC COLUMN TO ENHANCE THE COMPRESSIVE STRENGTH 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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Section :17A

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Dedicated

to

“Our parents”

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ABSTRACT

This research numerically represents the technique of increasing compressive strength of reinforced concrete (RC) column using Carbon fiber reinforced polymer (CFRP) under pure compressive load. Many researchers worldwide have extensively used fiber-reinforced polymer (FRP) strengthening materials to enhance the shear and flexural strengths of reinforced concrete RC columns. However, studies on compressive 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 columns under pure compressive loading with CFRP sheets with different configurations. Total 3 columns are modeled with the dimension of (6x12x24) in. One of them is performed as a control column and others are configured with different orientations of FRP sheets which are: fully wrapped, wrapped strips. Ultimate load, Displacement and cracking patterns has been measured from the numerical analysis. It is seen that CFRP performed better to increase the compressive strength compared to the control column. Fully CFRP wrapped column has increased the ultimate load-carrying capacity and ductility by about 179.08 % and 525.06 %. Finally, these results have been validated with the experimental result available in the literature. 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 columns.

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CHAPTER 1
INTRODUCTION

1.1 General

Columns are defined as vertical load-bearing members supporting axial compressive loads chiefly. This structural member is used to transmit the load of the structure to the foundation. In reinforced concrete buildings columns, floors, and columns are cast monolithically (Wang, et al., 2016). The bending action in the column may produce tensile forces over a part of cross-section. Still, columns are called compression members because compressive forces dominate their behavior.

A reinforced concrete column is a structural member designed to carry compressive loads, composed of concrete with an embedded steel frame to provide reinforcement. For design purposes, the columns are separated into two categories: short columns and slender columns.

Traditional concrete walls and columns tend to range from 3,000 to 5,000 psi, while 4,000 to 5,000 psi is needed for pavement. Concrete structures in colder climates require a higher psi to withstand more freeze/thaw cycles.

Factors on which strength of the column depends: -1. The Shape of the Column. 2. Size of the Column.3. Length of the Column.4. Cross-Section of the Column.

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.

Figure 1.1 shows how the percentage of fibers affects the net deflection with the increasing load.

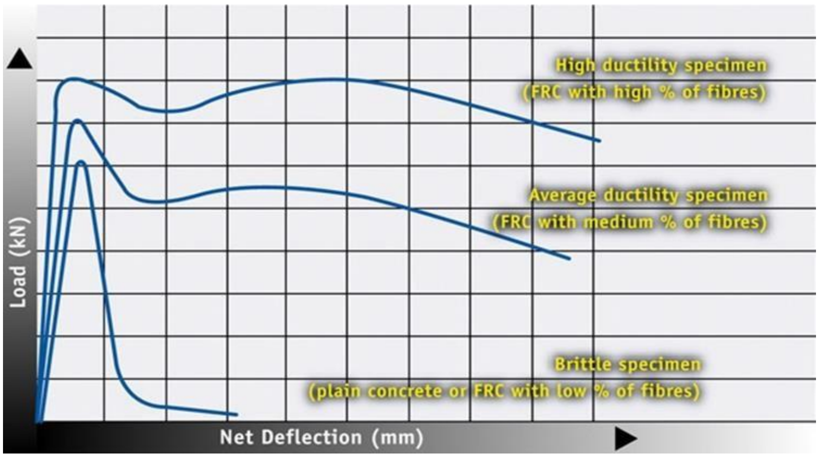
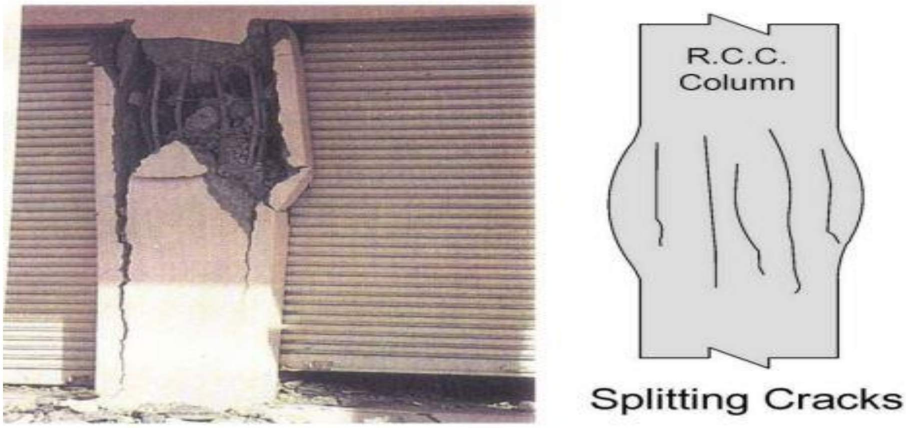


Figure 1:1 Load-Deflection Curves with different fiber percentage

Fiber-reinforced composite materials have proven their own advantages through many years of engineering practice and scientific research: light weight, high strength, and corrosion resistance, and they have been widely recognized and used. FRP includes: CFRP (carbon fiber), GFRP (glass fiber), AFRP (aramid fiber), BFRP (basalt fiber). After the concrete column is reinforced by CFRP, the lateral deformation of the concrete is obviously reduced, and the ultimate compressive strength and ductility of the concrete column are greatly improved.

Columns located at the perimeter of the building, when they subjected to the loads coming from the slab and columns, a compressional force is generated there which tends to twist the column with different angle of twist in either side.

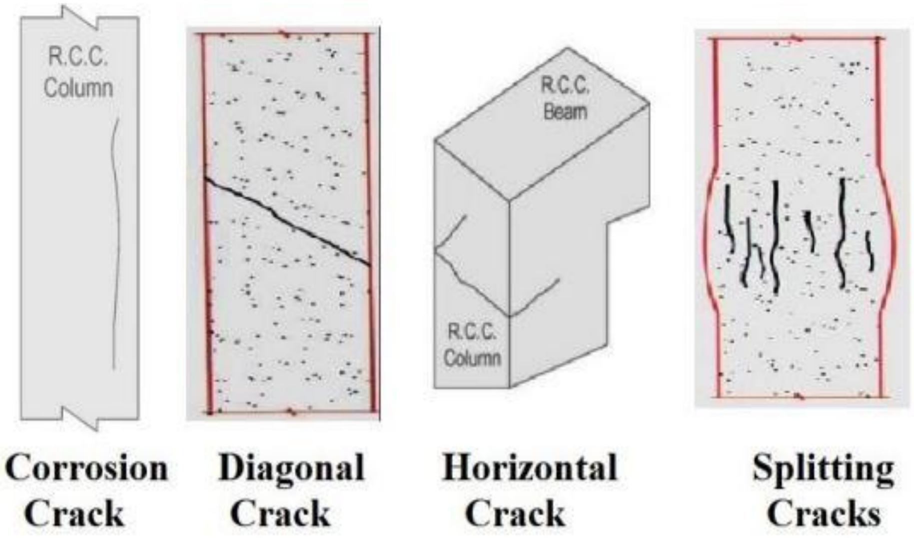


(1) Source: (https://buildingrepair.my/types-and-reasons-of-cracks-in-concrete-column/,)

(Accessed 11 Dec,2022)

Figure 1:2 Column cracks

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 column at its post cracking stage.



(2) Source: (https://theconstructor.org/concrete/types-cracks-concrete-columns/26433/,)

(Accessed 11 Dec,2022)

Figure 1:3 Column cracks

Weight ratio, non-corrosiveness. These characteristics make FRP the most effective material for increasing crack control phenomena and compressional 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 (Nahar, et al., 2019). 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.

1.2 Historic Development of Carbon 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.

The development of fiber reinforcement for concrete was very slow before the 1960s. Until then there were some papers describing the basic concept of using fibers for reinforcement in concrete mixes but there was no application. Nevertheless, research on carbon fibers had been conducted in the USA, UK, and Russia in the early 1950s. Actually, in Russia carbon fibers were not only under research but were also used in the construction industry.

However, this kind of fiber was found to be prone to alkaline attacks. In the late 1950’s Portland Cement Association started investigating fiber reinforcement.

1.3 Working Mechanism of Carbon Fiber Reinforced Polymer

Ordinary reinforced concrete can carry fewer amounts of loads than fiber reinforced concrete and develop cracks earlier than fiber reinforced concrete. The main mechanism of randomly distributed discontinuous fibers is to act as a bridge across the cracks that develop and provides some post cracking ductility. The Fibers are having to sufficiently strong and evenly distributed all over the member body (Goshtaei, et al., 2022). Thus, the load- bearing property of the concrete can be increased and thus members will allow more strain with the increasing stress. Fibers along with concrete and reinforcement will absorb more loads by increasing the toughness of the concrete.

Man-made fiber produced from steel, glass, synthetics, asbestos, and natural fibers such as cellulose, sisal, and jute are an example of the material that is being used as Carbon Fiber Reinforced Polymer (CFRP). Discontinuous fibers in the concrete do not enhance the tensile strength of the concrete but it is very effective to control the cracks of the member. This property of the Carbon Fiber Reinforced Polymer (CFRP) can be used in RC Column to resist the torsional effect produced from the twisting effect of the Column.

1.4 Characteristics of Carbon Fiber Reinforced Polymer (CFRP)

Carbon fiber, alternatively graphite fiber, carbon graphite or CF, is a material consisting of fibers about 510 μm in diameter and composed mostly of carbon atoms. The carbon atoms are bonded together in crystals that are aligned parallel to the long axis of the fiber. The crystal alignment gives the fiber high strength-to-volume ratio (making it strong for its size). Several thousand carbon fibers are bundled together to form a tow, which may be used by itself or woven into a fabric.

Carbon fiber is a high-tensile fiber or whisker made by heating rayon or polyacrylonitrile fibers or petroleum residues to appropriate temperatures. Fibers may be 7 to 8 microns in diameter and are more that 90% carbonized.

These fibers are the stiffest and strongest reinforcing fibers for polymer composites, the most used after glass fibers. Made of pure carbon in form of graphite, they have low density and a negative coefficient of longitudinal thermal expansion.

Carbon fibers are very expensive and can give galvanic corrosion in contact with metals. They are generally used together with epoxy, where high strength and stiffness are required, i.e. race cars, automotive and space applications, sport equipment.

Depending on the orientation of the fiber, the carbon fiber composite can be stronger in a certain direction or equally strong in all directions. A small piece can withstand an impact of many tons and still deform minimally. The complex interwoven nature of the fiber makes it very difficult to break.

1. Physical strength, specific toughness, light weight.
2. Good vibration damping, strength, and toughness.
3. High dimensional stability, low coefficient of thermal expansion, and low abrasion.
4. Electrical conductivity.
5. Biological inertness and x-ray permeability.

6. Fatigue resistance, self-lubrication, high damping.
7. Electromagnetic properties.
8. Chemical inertness, high corrosion resistance.

1.5 Classification of Carbon Fiber

Based on modulus, strength, and final heat treatment temperature, carbon fibers can be classified into the following categories:

- Based on carbon fiber properties,
- Based on precursor fiber materials,
- Based on final heat treatment temperature

1.5.1 Based on carbon fiber properties, carbon fibers can be grouped into

- Ultra-high-modulus, type UHM (modulus >450Gpa)
- High-modulus, type HM (modulus between 350-450Gpa)
- Intermediate-modulus, type IM (modulus between 200-350Gpa)
- Low modulus and high-tensile, type HT (modulus < 100Gpa, tensile strength > 3.0Gpa)
- Super high-tensile, type SHT (tensile strength > 4.5Gpa)

1.5.2 Based on precursor fiber materials, carbon fibers are classified into:

- PAN-based carbon fibers
- Pitch-based carbon fibers
- Mesosphere pitch-based carbon fibers
- Isotropic pitch-based carbon fibers
- Rayon-based carbon fibers
- Gas-phase-grown carbon fibers

1.5.3 Based on final heat treatment temperature, carbon fibers are classified into:

- High-heat-treatment carbon fibers (HTT), where final heat treatment temperature should be above 2000C and can be associated with high-modulus type fiber.

- Intermediate-heat-treatment carbon fibers (IHT), where final heat treatment temperature should be around or above 1500C and can be associated with high-strength type fiber.

- Low-heat-treatment carbon fibers, where final heat treatment temperatures not greater than 1000C. These are low modulus and low strength materials.

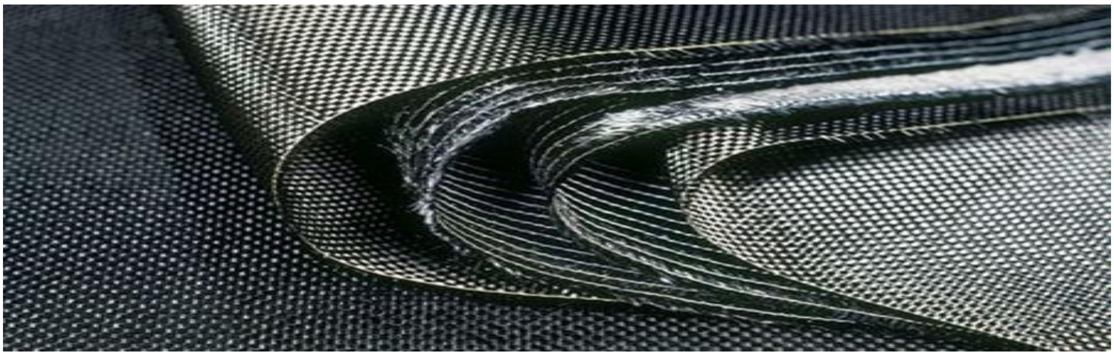
Fiber Reinforced Polymers (FRP) are unique composite materials in many respects. FRP can be formulated to be corrosion, abrasion, and UV resistant, as well as, smoke and fire retardant. FRP is often a cost-effective choice in many industrial applications; they have long life cycles and have demonstrated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

Here are some of the characteristics of Fiber Reinforced System.

1.6 FRP Composites

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

- Carbon fiber reinforced concrete (CFRP)



(Source:https://www.mpnc.net.au/news/2018/9/4/ecco-ripley-3smbn-n3pms-hsph7-6pbhj-efmrk-hzj5r-j6c6y-yj4ka-4ntbf-jzgs8, (Accessed 11 Dec,2022)

Figure 1:4 Carbon Fiber Polymer Composites

1.7 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 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.

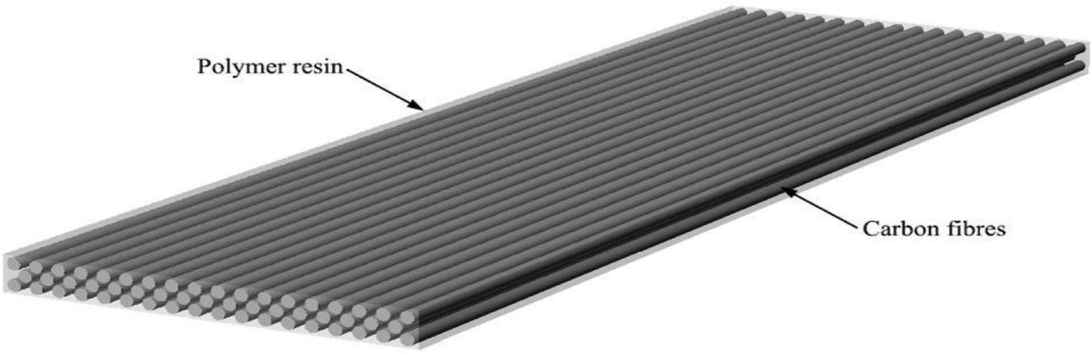


Figure 1:5 Typical structure of Carbon Fiber Reinforced Polymer (CFRP)

(Source: https://images.app.goo.gl/MbyenB38dUUjt1jh6, Accessed 11 Dec,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.

1.8 Uses of CFRP Composites in the Modern World

Applications of CFRP composites are increasing day by day. In many sectors like Aerospace engineering, Automobile engineering, Civil engineering, Sports; CFRP are performing brilliantly.

1.8.1 CFRP in Aerospace Engineering

The Airbus A350 XWB is built of 52% CFRP, including wing spars and fuselage components, overtaking the Boeing 787 Dreamliner, for the aircraft with the highest weight ratio for CFRP, which is 50%.This was one of the first commercial aircraft to have wing spars made from composites. The Airbus A380 was one of the first commercial airliners to have a central wing box made of CFRP; it is the first to have a smoothly contoured wing cross-section instead of the wings being partitioned span-wise into sections. This flowing, continuous cross-section optimizes aerodynamic efficiency.

1.8.2 CFRP in Civil Engineering

CFRP has become a notable material in structural engineering applications. Studied in an academic context as to its potential benefits in construction, it has also proved itself cost-effective in a number of field applications strengthening concrete, masonry, steel, cast iron, and timber structures. Its use in industry can be either for retrofitting to strengthen an existing structure or as an alternative reinforcing (or pre-stressing) material instead of steel from the outset of a project.

Retrofitting has become the increasingly dominant use of the material in civil engineering, and applications include increasing the load capacity of old structures (such as bridges) that were designed to tolerate far lower service loads than they are experiencing today, seismic retrofitting, and repair of damaged structures. Retrofitting is popular in many instances as the cost of replacing the deficient structure can greatly exceed the cost of strengthening using CFRP.

Applied to reinforced concrete structures for flexure, CFRP typically has a large impact on strength (doubling or more the strength of the section is not uncommon), but only a moderate increase in stiffness (perhaps a 10% increase). This is because the material used in this application is typically very strong (e.g., 3000 MPa ultimate tensile strength, more than 10 times mild steel) but not particularly stiff (150 to 250 GPa, a little less than steel, is typical). As a consequence, only small cross-sectional areas of the material are used. Small areas of very high strength but moderate stiffness material will significantly increase strength, but not stiffness. CFRP can also be applied to enhance the shear strength of reinforced concrete by wrapping fabrics or fibers around the section to be strengthened. Wrapping around sections (such as a bridge or building columns) can also enhance the ductility of the section, greatly increasing the resistance to collapse under earthquake loading. Such 'seismic retrofit' is the major application in earthquake-prone areas since it is much more economic than alternative methods.

If a column is circular (or nearly so) an increase in axial capacity is also achieved by wrapping. In this application, the confinement of the CFRP wrap enhances the compressive strength of the concrete (Tuken & Siddiqui, 2013). However, although large increases are achieved in the ultimate collapse load, the concrete will crack at only slightly enhanced load, meaning that this application is only occasionally used. Specialist ultra-high modulus CFRP (with tensile modulus of 420 GPa or more) is one of the few practical methods of strengthening cast-iron columns. In typical use, it is bonded to the tensile flange of the section, both increasing the stiffness of the section and lowering the neutral axis, thus greatly reducing the maximum tensile stress in the cast iron.

1.9 Properties of CFRP composites

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 friction coefficient and good wear resistance, chemical and dimensional stability.

1.9.1 The physical properties of CFRP

The density of CFRP ranges from 1.25 to 2Bg/cm3, which is 1/6 to 1/4 of steel. Low density can reduce weight and facilitate transportation and installation. CFRP should not be used in high temperature structures. The softening temperature of CFRP is called "Grass Transition Temperature Tg", which mainly depends on the type of resin, usually

65~122°C. When the temperature exceeds Tg, the elastic modulus of CFRP will be greatly reduced.

1.9.2 Mechanical properties

As we all know, the main force direction of CFRP is the direction mainly parallel to the fiber, which is the axial direction. Tensile strength, compressive strength and bonding properties are the main mechanical properties of CFRP.

1.9.3 Tensile strength

Fiber is the basis of FRP tensile strength, and resin mainly plays a certain auxiliary role. The stress-strain curve of fiber, resin and CFRP. The stress-strain relationship of CFRP is linear elastic relationship. The ultimate strength of fiber is higher than that of CFRP. The ultimate tensile strain of the resin is higher than the ultimate tensile strain of CFRP and fiber, which indicates that the resin breaks after the fiber breaks.

1.9.4 Compressive strength

The compressive strength of CFRP is lower than the tensile strength. The compressive strengths of GFRP, CFRP, and AFRP are 55%, 78%, and 22% of the tensile strength, respectively. In most cases, the compressive strength of CFRP is proportional to the tensile strength of CFRP.

- **Creep fracture**

The creep fracture of CFRP is the sudden fracture of CFRP under long-term constant load. And the endurance time of CFRP gradually decreases with the increase of the load duration.

- **Fatigue performance**

CFRP has good fatigue resistance when the fiber and resin are well bonded, and it is less affected by external factors.

- **Durability**

The test results show that CFRP exhibits good durability

The significance of CFRP wrap and CFRP laminate strips in retrofit concrete columns

Whether it is a building or a structure, the most important load-bearing component of a building structure is the column structure, and the reliability and comfort of the building are closely related to it. Reinforced concrete columns are currently the most used column structure in the main structure of buildings and structures in my country.

CFRP wrapping concrete columns can effectively improve the axial compressive bearing capacity of the columns. The use of CFRP can significantly increase the compressive strength of concrete and improve the ductility of concrete. At the same time, for concrete structure reinforcement and reconstruction projects, CFRP reinforced concrete column technology has many advantages (high strength and light weight, durability, ease of construction, etc.). The reinforcement method of CFRP reinforced concrete columns has been applied in more and more practical projects.

In projects where carbon fiber cloth is used for reinforcement and reconstruction, due to cost and construction considerations, many structures are currently reinforced with carbon fiber plates. In many practical projects, the method of reforming and retrofit carbon fiber plates is also used, and it has also been proved to improve the bearing capacity and ductility of structural members. The use of carbon fiber plates for reinforcement can effectively increase the utilization rate of carbon fiber and has good economic benefits. Especially in terms of construction, the use of carbon fiber plates reinforcement requires little construction site and construction space, which can effectively and flexibly organize construction

Figure 1.3 shows the general behavior of CFRP 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 carbon and glass have been shown in Table 1.1.

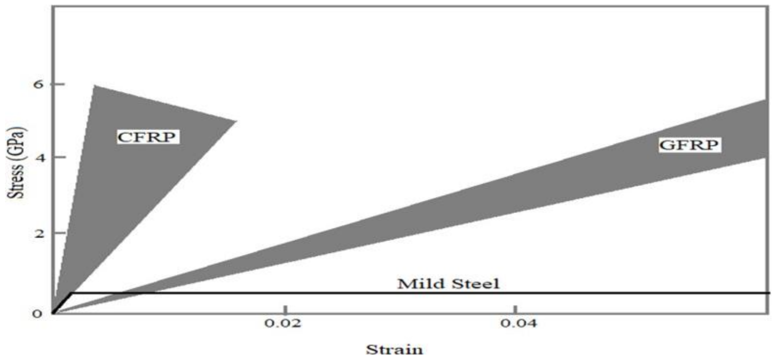


Figure 1:6 Typical stress-strain relation for different FRPs and normal steel

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

In this study carbon fibers (CFRP) and was used for strengthening of RC column to withstand the cracks develop for the twisting effect of RC column,

Table 1:1 Some Typical Properties Of CFRP

Type of Fiber	Tensile Strength (psi)	Compressive Strength (psi)	Elongation Capability	Stiffness (modulus of elasticity- psi x 106	Weight per Cubic Foot
Carbon fiber	470,000	338,400	1.4%	33.0	108.9

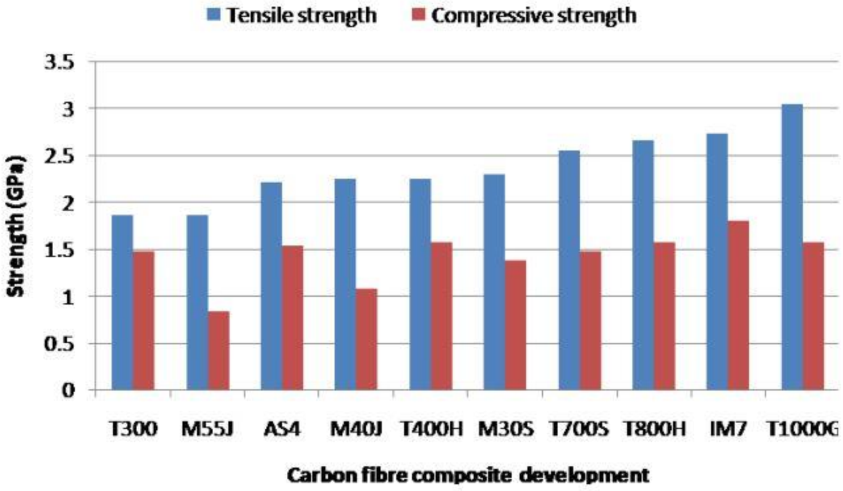


Figure 1:7 Tensile & compressive strength of unidirectional carbon fiber composites

(Source:http://home.iitk.ac.in/~mohite/axial_compressive.pdf, Accessed 11 Dec,2022)

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 paper, the behavior and performance of reinforced concrete column strengthened with bonded fibers especially with Carbon fibers (CFRP).

1.10 The Objective of the Research

The objectives of the investigation are:

- To model an RC column using ABAQUS software and make a Finite Element (FE) analysis.
- To investigate the performance of CFRP to increase the compressive strength using the FE analysis
- To investigate the effective orientation of FRP composites using the FE analysis.
- To examine the failure patterns of RC columns 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

This chapter should describe the relevant literature. It should present what has already been studied on the research topic. The relevant works should be organized in a structured manner. Relation between the previous works and the thesis work is particularly important to discuss in this chapter. The existing works should be analyzed thoroughly to point out their both strong and weak points. There is some research conducted over two decades on the torsion strengthening of RC Columns using Fiber Reinforced Polymer (FRP), they are discussed below.

2.2 Previous Background of the Study

(Leeladhar Reddy, et al., 2019) said that retrofitting is the process of strengthening the structure or the structural elements using different techniques. It is of two types: Global retrofitting and Local retrofitting. The main target of global retrofitting is to provide seismic resistance. The Seismic waves that reach the earth’s surface cause an earthquake. Sudden Seismic forces is the major problem faced in the construction field, so to resist the effect of seismic force on the building addition of shear walls was introduced to the structure. Local retrofitting concentrates on improving the load resistance of the member by using advanced techniques like jacketing to structural members i.e., column, column, & column-column joint. Reinforced Concrete Jacketing, Steel jacketing and fiber reinforced polymer jacketing are the advanced techniques available for retrofitting which are used to increase the flexural strength and shear strength of the column or column. Fiber Reinforced Polymer (FRP) is the composite material that is increasingly used in the construction industry.

Usage of FRP materials have been increased in recent years because of their light weight and high strength and resistance to corrosion. In retrofitting FRP jacketing is used because carbon fiber is flexible and made to contact the surface tightly for a high degree of confinement due to its high strength and modulus of elasticity. The main advantage of using FRP wrapping in columns is to increase the ductility, increase in flexure, shear strength and rapid installation.

In the present study, the structure is designed and analyzed using different loading conditions. Some of the structural elements were failed, at this stage we have to re-design the structure but the other alternative for this is to identify the failed structural elements and retrofit them with the suitable technique to increase the load carrying capacity of that structural element.

(Lewangamage, et al., 2017) , (Choo, 2005), (Ghanem, 2016) found that the use of carbon fiber reinforced polymer CFRP materials is considered as a very effective retrofitting technique for reinforced concrete columns, still it is the identification of cost reduction strategies that draws most of the attention since the use of CFRP materials is considered as more expensive than any other retrofitting method. Providing partial confinement in place of full confinement which is the current practice may be a viable option that allows for considerable cost savings while maintaining the required structural capacity. Although CFRP technology has been in use for several decades, some countries still do not have adequate technical know-how to use this technique effectively. As there are several design guidelines available globally, it is quite unclear which design guideline will provide an economical design while maintaining the required factor of safety. This paper presents an experimental study conducted using 17 specimens to investigate the strength increments due to external CFRP confinement of reinforced and unreinforced concrete columns. Reinforced concrete columns were provided with both full and partial confinement to study their strength and ductility increments. The volumetric ratio of CFRP was kept constant for partially confined columns to study the effect of the jacket arrangement pattern. The experimental failure loads obtained were reviewed against the theoretical values calculated using ACI and fib guidelines, to investigate the overall safety factors available when using each design guideline. The experimental results showed considerable strength and ductility increments in all of the fully and partially confined specimens.

Although the volumetric ratio of CFRP was kept same for all partially confined columns, it was observed that depending on the jacket location, the strength and ductility increments would vary. It was also observed that both design guidelines give for fully confined reinforced concrete columns, a factor of safety exceeding 1.5.

(Saeed, 2020) said that the use of FRP materials in strengthening and repairing of reinforced concrete (RC) structures has increased in the past two decades. Recently, FRP materials have become one of the most used materials in rehabilitation engineering. For seismic retrofitting of RC structures, usually the process involves strengthening or repairing the vertical support elements of the buildings or bridges. Several studies focused on the use of FRP materials in strengthening and repairing RC columns. Externally bonded (EB) FRP sheets or laminates and near-surface-mounted (NSM) FRP rods have been used for enhancing the strength and ductility of RC columns. Although glass FRP (GFRP) and basalt FRP (BFRP) rods have been used in flexural strengthening of RC columns, NSM-CFRP rods have not been used yet. In addition, studies in the use of CFRP ropes in flexural strengthening or repairing of RC columns are not available.

To address these gaps, an experimental investigation was conducted on the use of CFRP materials in strengthening and repairing RC columns. The investigation consisted of three main parts. The three parts focused on strengthening and repairing slender RC columns using CFRP materials. The first part of the investigation focused on the use of CFRP sheets, rods, and ropes in flexural strengthening of RC columns. Half scale square (150 x 150 mm) RC columns were fabricated and tested. Each specimen consisted of two 1.065-meter-long columns connected in the middle by a stiff element (concrete stub). All columns were designed based on older codes (pre-1970s). The specimens were (1) as built specimen, (2) strengthened with CFRP confinement only, (3) strengthened with CFRP confinement and NSM-CFRP rods, and (4) strengthened with CFRP confinement and NSM-CFRP ropes (two specimens). Another specimen was strengthened with EB-CFRP sheets. The results showed that both EB and NSM techniques can effectively be used in strengthening slender RC columns. In addition, CFRP ropes are very effective in strengthening RC columns. The strength enhancement ranged from 35% to 60%. Finally, a theoretical model was created to predict the load-displacement response of RC columns strengthened with EB-CFRP sheets and NSM-CFRP rods and ropes. The theoretical results showed good agreement with the experimental results. The second part of the investigation focused on the use of CFRP sheets and ropes in repairing damaged RC columns. Recently, RC columns have been upgraded and strengthened with FRP confinement all around the globe. Future cases of repair will likely encounter RC columns that were strengthened previously with FRP confinement. However, studies on repairing damaged columns that were enhanced by confinement before damage are not currently available. Moreover, there is a vital need for an emergency repair technique that can be used to rapidly repair damaged columns of essential structures after a seismic event. In this study, the time required to complete the repair was a key factor to propose a rapid CFRP-based repair technique. A total of four specimens, each one representing two columns, were fabricated and tested. The technique was applied to square RC columns (150 mm x 150 mm x 1,065 mm) subjected to combined axial and cyclic lateral loads. The process of applying the repair technique was completed in three days. Test results showed that the proposed repair technique was effective not only by restoring the original strength, but also by improving the strength significantly. Moreover, the measured and idealized load-displacement response showed that the ductility of the repaired column was reasonably sufficient. The proposed technique appears promising and may be considered as a permanent repair technique.

The third part of the investigation focused on the tensile strength of CFRP ropes anchored to concrete using chemical epoxy. One of the major problems with using fiber reinforced polymer (FRP) in strengthening reinforced concrete (RC) structures is premature debonding of FRP. Anchoring FRP materials to concrete has become associated with most of the strengthening techniques. One of the anchoring techniques is using handmade anchors made from FRP materials. In previous studies, most FRP anchors were made from rolling pre-cut FRP sheets with short embedment (mm) as they were used for flexural or shear strengthening of RC columns. In the present study, FRP anchors were made from carbon fiber reinforced polymer (CFRP) ropes and had long embedment to be used for flexural strengthening of RC columns. A total of twenty-one pullout tests were conducted on CFRP rope anchors bonded to concrete using chemical epoxy. The test parameters included embedment lengths of 45 mm, 90 mm, 135 mm, 180 mm, 270 mm, and 315 mm; anchor hole diameters of 12.7 mm, 19.1 mm, and 25.4 mm; and two epoxy types, Hilti 500 and Master Brace SAT 4500. Test results showed that the pullout strength of CFRP anchors increased with the increase in embedment length, and no significant effect of the hole diameter on the pullout strength was observed. However, the bond strength increased with decreasing embedment length and hole diameter. For shorter embedment lengths, the distribution of the bond stress along the length of the anchor is expected to be more uniform than that of anchors with longer embedment lengths. The average bond stress (strength) is calculated by dividing the maximum pullout force by the embedment length. Therefore, increasing the embedment length without significant improvement in the pullout load results in lower bond strength. The observed pullout results and failure modes were compared to the predictions using available models. Finally, a modified model was proposed to predict the pullout strength of CFRP rope anchors.

(Wang, et al., 2016) used Fiber-reinforced polymer (FRP) as external reinforcement. The behavior of fiber-reinforced polymer (FRP) tube reinforced concrete (FTRC) columns under different loading conditions was investigated in this study. Four groups of 16 specimens were cast and tested. Specimens in the first group (the reference group) were reinforced with longitudinal steel bars and steel helices (Group REF). Specimens in the second group were reinforced with intact glass FRP tubes (Group IT). Specimens in the third group were also reinforced with intact glass FRP tubes. In addition, polymer grid was embedded into the concrete cover to reduce the cover spalling (Group ITG). Specimens in the fourth group were reinforced with perforated glass FRP tubes (Group PT). One specimen from each group was tested under concentric loading, one under 25-mm eccentric loading, one under 50-mm eccentric loading, and one under four-point loading. Results from the experimental study show that FRP tubes significantly increase the load-carrying capacity and ductility of FTRC specimens. Group ITG specimens performed better than the other groups of specimens. Experimental and analytical interaction (P−M) diagrams also show the enhanced performance of FTRC specimens.

(Haji, et al., 2019) said that the most important phenomenon that threatens the stability and health of structures in different parts of the world is the occurrence of an earthquake with varying intensity and magnitude.

The most dangerous type of failure in structures is shear failure, which could occur in short columns. Consequently, such columns, with the potential of failure in shear, must be retrofitted. This paper explores three new methods for strengthening RC circular short columns, including the Near Surface Mounted (NSM), externally bonded with new pattern and an innovative hybrid strengthening technique (using near-surface mounted method in the form of spiral grooves filled with CFRP hand-made bar in composition with externally bonded CFRP sheet) and compare them with two common methods of strengthening (full and partial wrapping). Six circular short columns were constructed, strengthened and tested under constant axial load and cyclic lateral loading. An analytical procedure was used to predict the behavior of the columns. A good correlation was observed between analytical values and experimental results. An innovative hybrid strengthening method and externally bonded method with new pattern showed higher values in strength, energy absorption, ductility and stiffness compared to existing methods.

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 column using CFRP composites

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

(1) (Source: https://images.app.goo.gl/1cfJvr5CMzBQ82V87, Accessed 11 Dec,2022)

(2) (Source: https://images.app.goo.gl/Wf8mpdRPDc6P2CDp9, Accessed 11 Dec,2022)

(3) (Source: https://images.app.goo.gl/VBSfFG4KUhd77Khq9, Accessed 11 Dec,2022)

Figure 2:2 (1), (2), (3) Strengthening process of RC column using CFRP composites

2.4 Background and Present State of The Problem

From the background work, it is seen that increasing compressive 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 compressive 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 based on 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, ABAQUS is used 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 enhancement of axial compressive strength of Rectangular Circular Column using CFRP. Total 3 column has been analyzed to determine the compressive strength which are:

- Normal RC column
- RC column with fully CFRP wrapped
- RC column with CFRP wrapped strip

All the column dimensions are the same (6x12x24) in and the same amount of reinforcement are used. The load cell is placed on the top part which creates an axial compression on the column. The area of the load cell is (9x15) in.

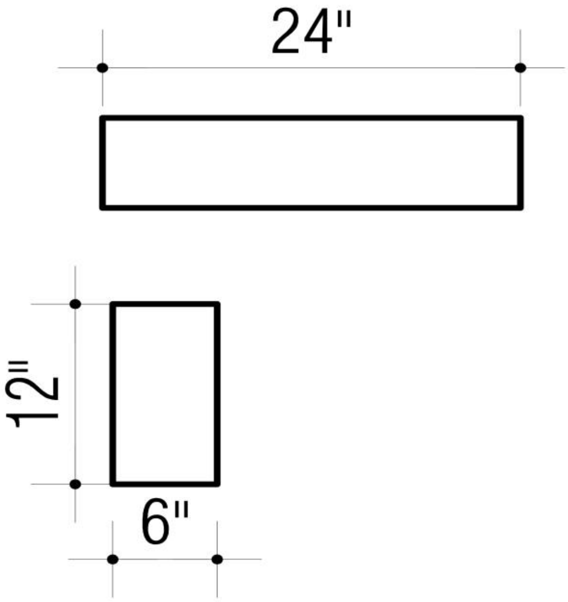


Figure 3:2 Designed column plan view

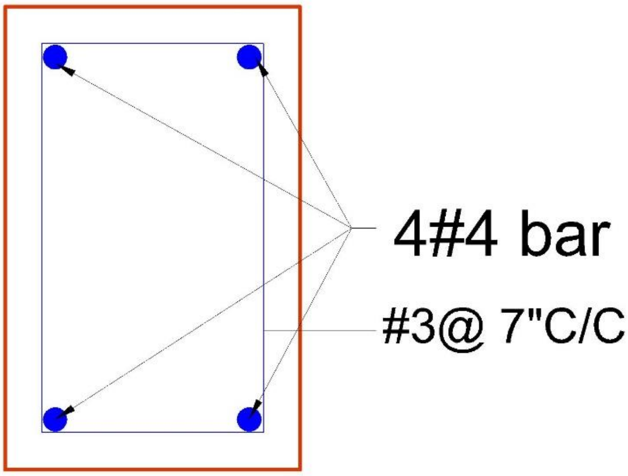


Figure 3:3 Main column cross sectional profile

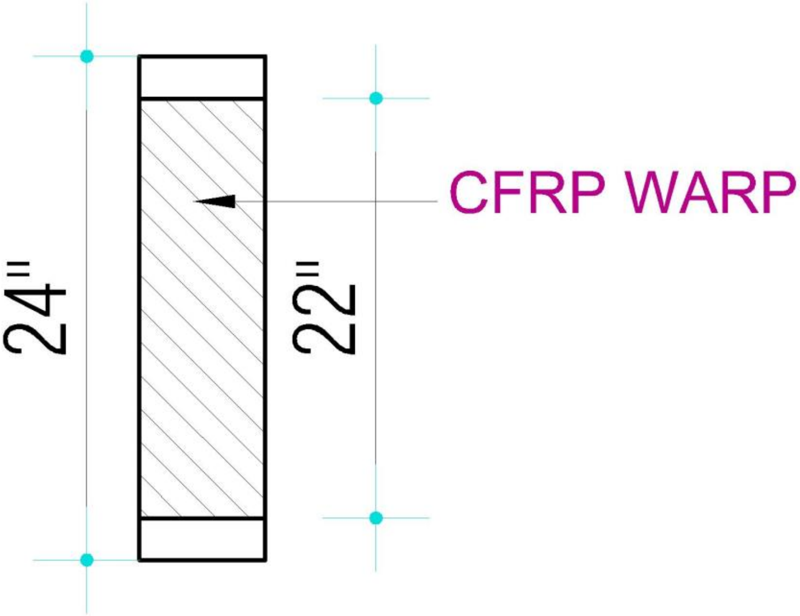


Figure 3:4 Designed RC column with fully CFRP wrapped

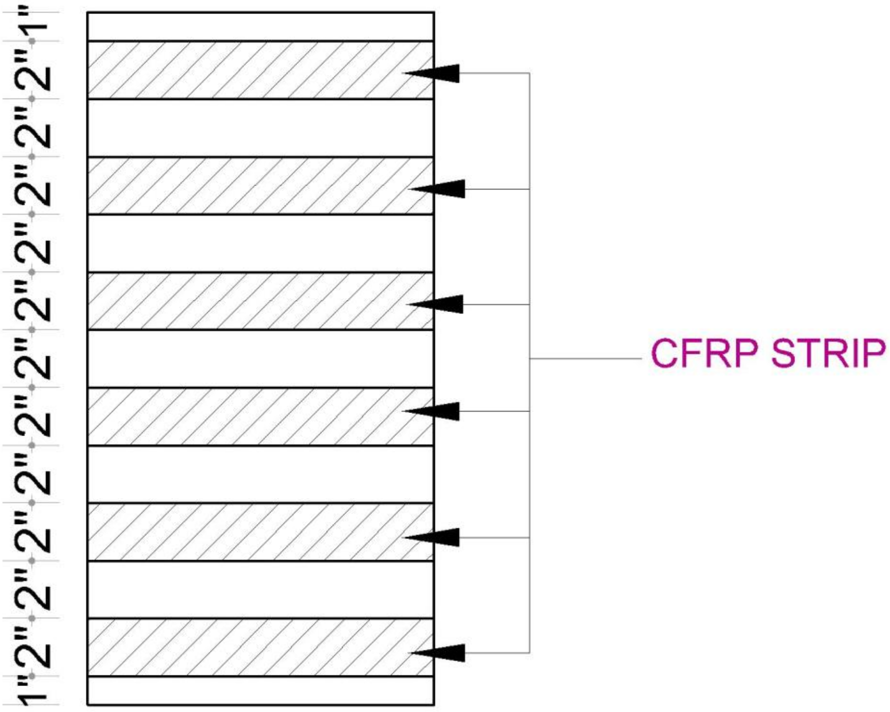


Figure 3:5 Designed RC column with CFRP strip

3.5 Material Properties of Modeling

For modeling in ABAQUS anyone must define the material properties of the column. 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 (3.6) shows typical uniaxial compressive and tensile stress-strain curve for concrete.

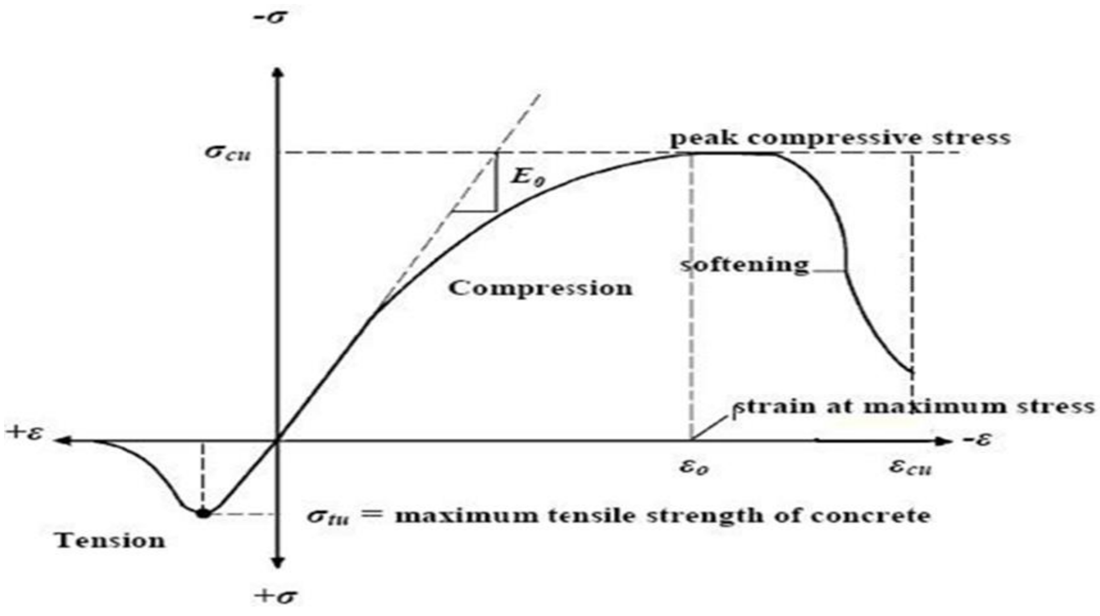


Figure 3:6 Typical uniaxial compressive and tensile stress-strain curve for concrete.

(Source: https://images.app.goo.gl/pnkxe5skBiNVnDfF7, Accessed 11 Dec,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 3.7. 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

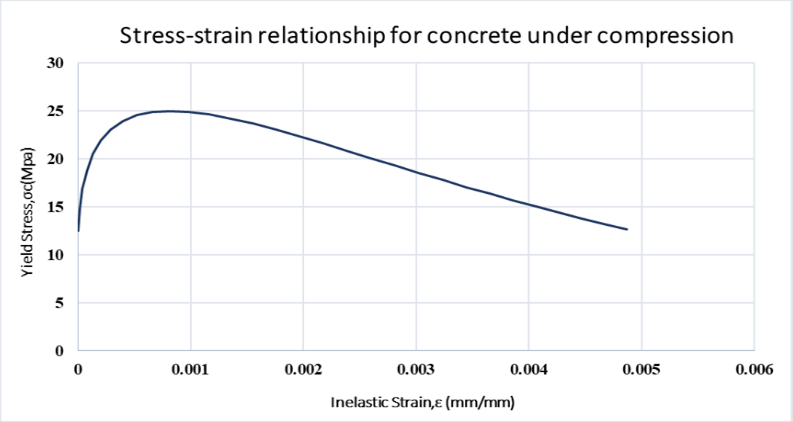


Figure 3:7 Stress-strain relationship for concrete under uniaxial compression.

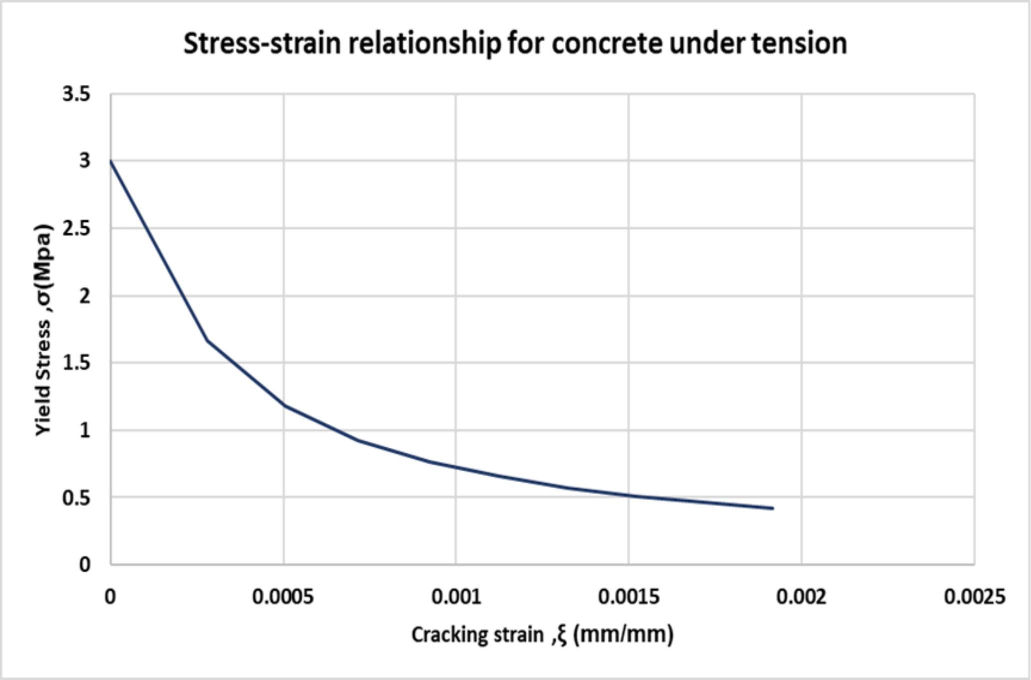


Figure 3:8 Stress–strain relationship for concrete under unit-axial tension.

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.

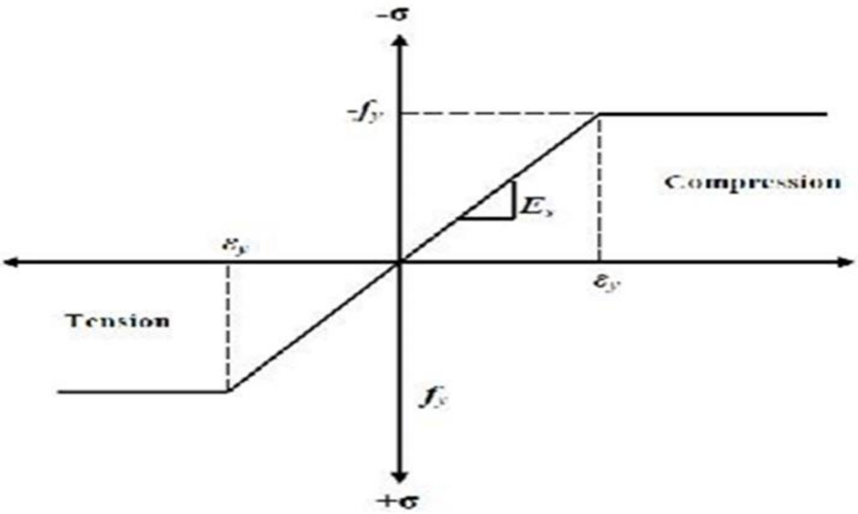


Figure 3:9 Stress-strain curve for steel reinforcement.

Table 3:3 Properties of reinforcing steel bars for column.

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 t/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 t/mm^3	7.8e-8

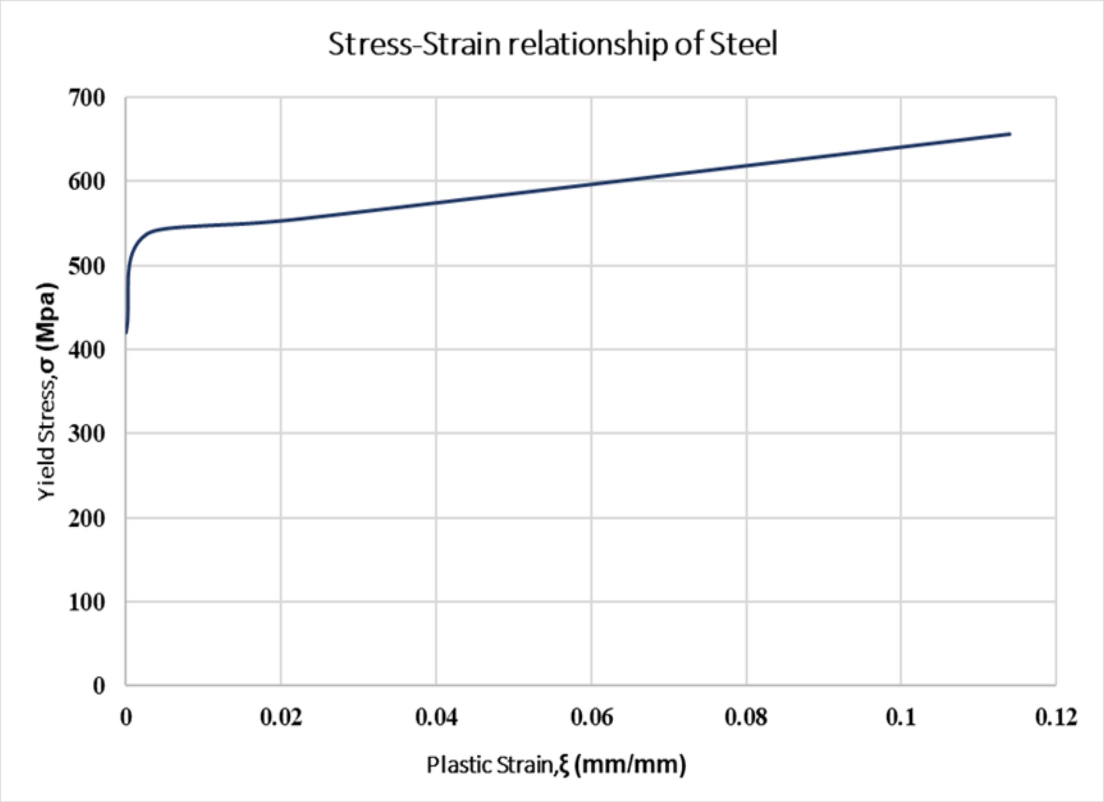


Figure 3:10 Stress-strain relationship for steel used in ABAQUS

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 column 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 3.11 and the integration points are numbered according to Figure 3.12. 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.

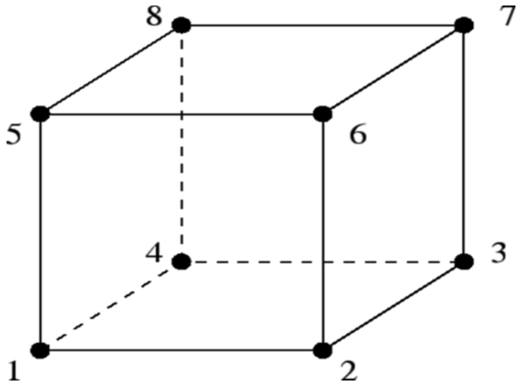


Figure 3:11 Node brick element

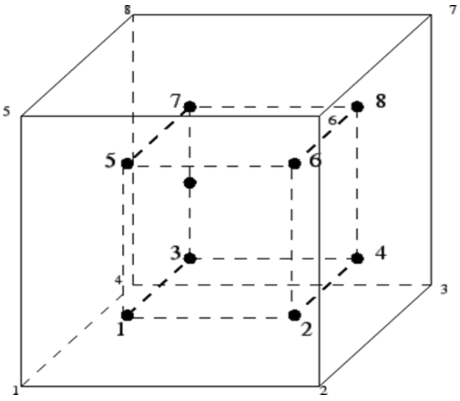


Figure 3:12 2x2x2 integration point scheme in hexahedral elements

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 concrete column are made to facilitate load application and meshing. The steel reinforcement of size 1220 mm is modeled as two-node truss elements connected to the nodes of adjacent solid elements. Stirrup's diameter is 225 mm are also designed with a two-node truss element. Linear 3D three-node triangular facet thin shell elements are used to model the composites.

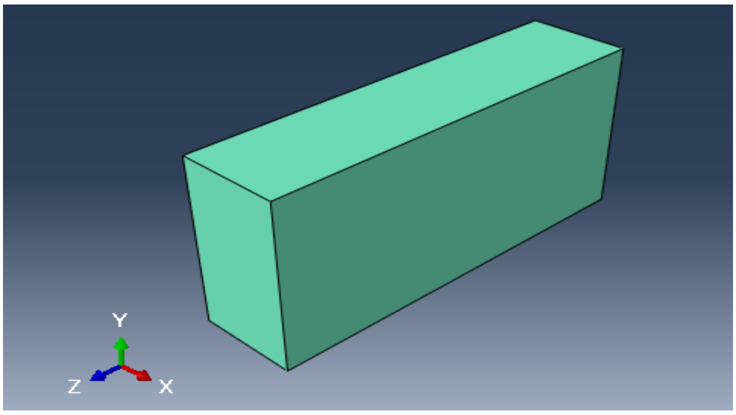


Figure 3:13 3D-Solid column designed in ABAQUS

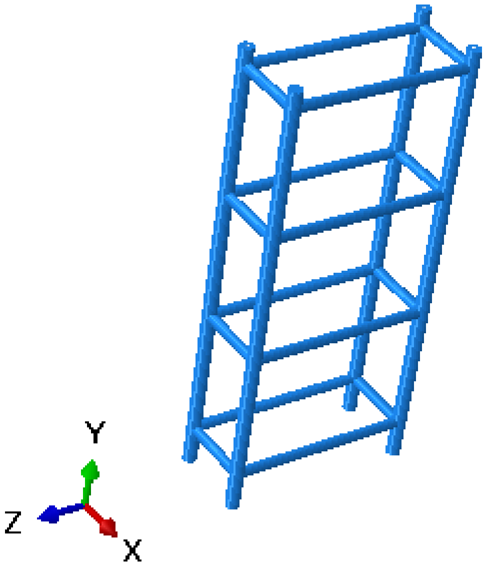


Figure 3:14 Reinforcement and Stirrups modelling

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 that it does not require to mash.

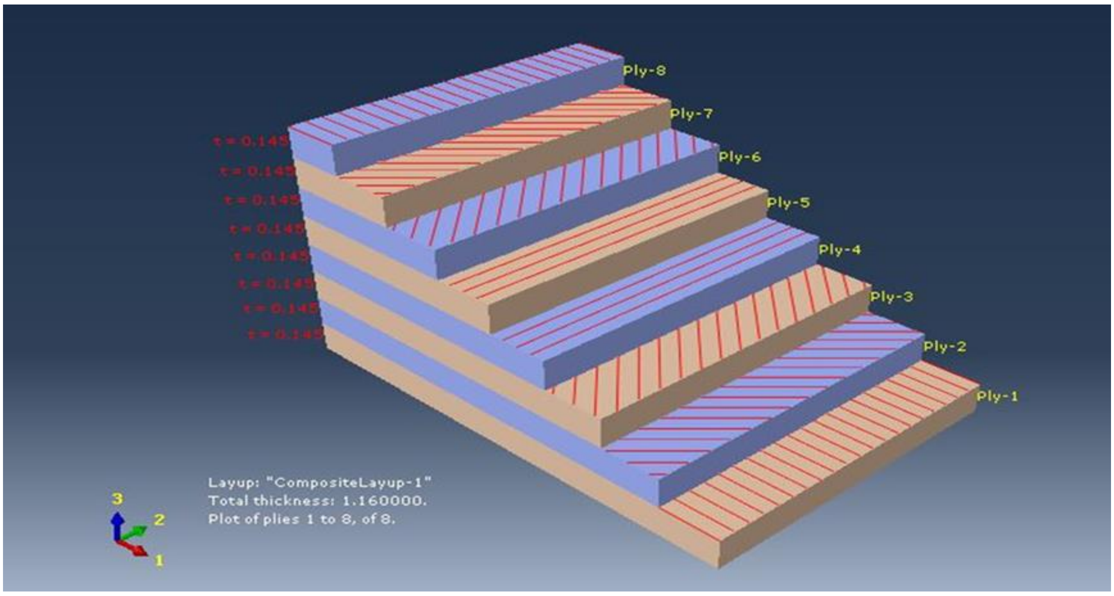


Figure 3:15 Composite ply layers orientation

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 column and reinforcement. Rigid body constraint is used to make a surface-surface contact between the column and load-cells and supports. CFRP is assembled with a column with Lamina type bonding. Some reference points are created to place the load for collecting output data.

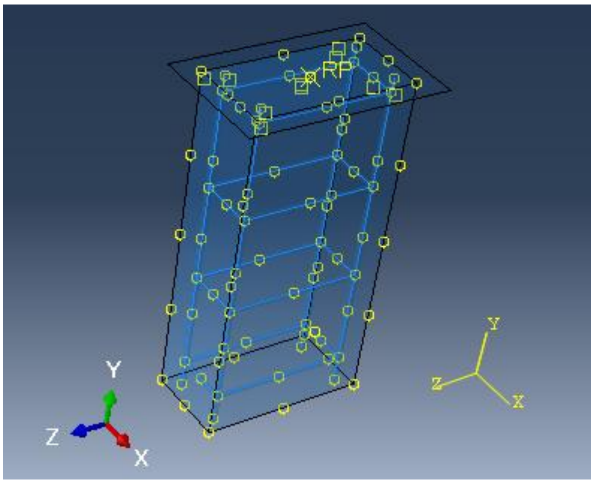


Figure 3:16 Constraint's profile used in ABAQUS modeling

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.

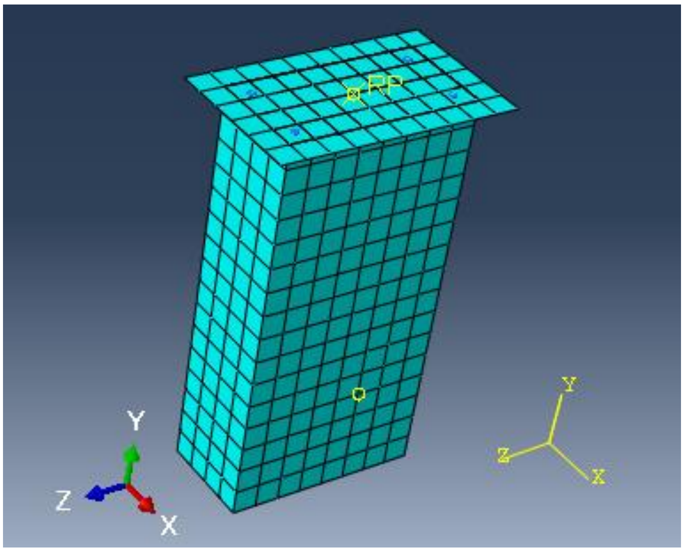


Figure 3:17 Meshed Column

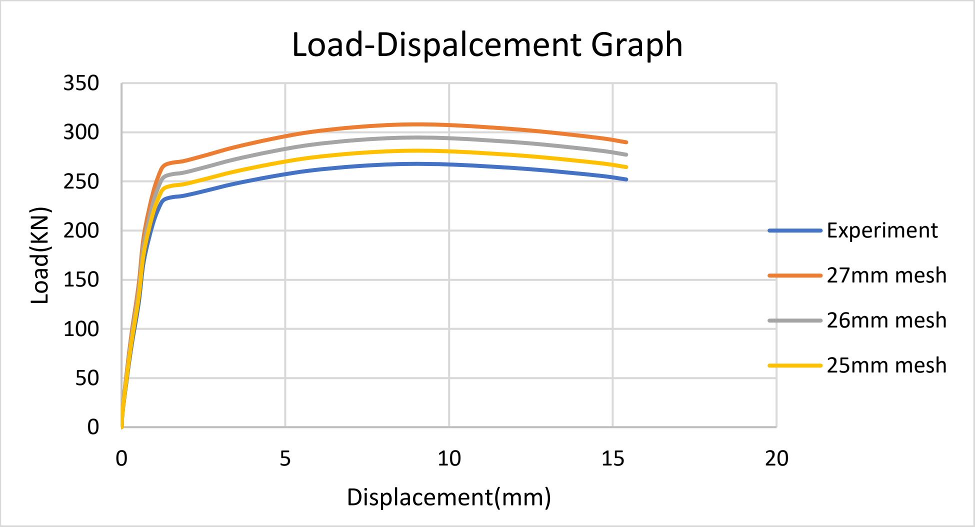


Figure 3:18 Load vs Displacement graph for finding optimum mesh.

From the Load vs Displacement Graph, it is clear that 26mm and 27mm mesh gives a constant result, optimum mesh, 25 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. A constant displacement of 15mm has been applied at a rate of 1mm/min. This will create a axial compressive force at both ends of the column and a compression will be produced due to the load-cell. A fixed support has been placed at the bottom of the column. 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.

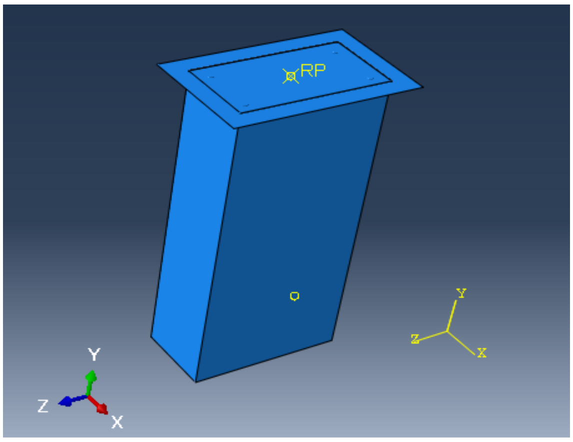


Figure 3:19 Final designed column model in ABAQUS

3.7 Modeled column Codes and Legends

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

Column Code	**Legends**
Control Specimen	CS
Fully CFRP wrapped Column	FCWC
CFRP wrapped strip Column	CWSC

CHAPTER 4

RESULTS AND DISCUSSION

4.1 General

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

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

4.2 Effect of CFRP on Increasing Compressive Strength

It is observed that introducing CFRP has increased the compression carrying capacity of the column compared to the control column. The displacement decreased compared to the control specimen and load-carrying capacity also increased.

4.2.1 Control Specimen Vs Fully CFRP Wrapped Column

Table 4:1 Ultimate load and Ductility data for control and Fully CFRP wrapped column

Specimen	**Ultimate load (KN)**	**Increase in Load %**	**Displacement(mm)**	**Increase in Ductility (mm) %**
CS	282		8.66	
FCWC	787	179.08	54.13	525.06

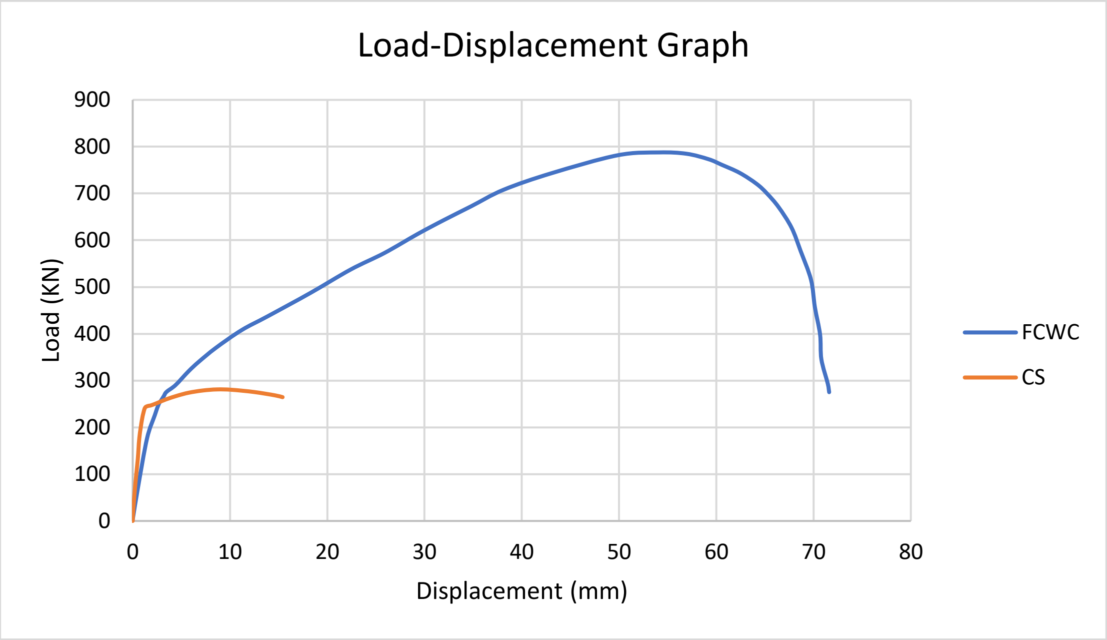


Figure 4:1 Load vs Displacement graph between Control Column and Fully CFRP wrapped Column

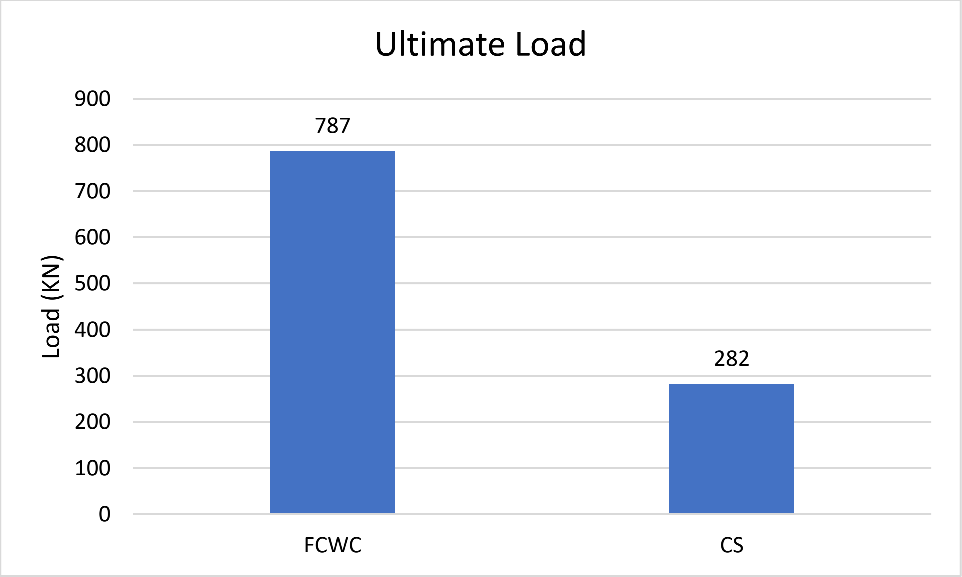


Figure 4:2 Ultimate load-carrying capacities of control and fully CFRP wrapped column.

4.2.2 Discussion

From the result, it is clear that FCWC has more load resistance than CS. Load resistance of FCWC has increased up-to 193% than CS and Ductility increased up-to 525%. For CS, after the yielding of the reinforcement an ultimate peak value of load is noticed and after that ultimate failure of the column occurs. But for FCWC after the linear increase of load instead of yielding reinforcement CFRP start carrying load and a high increase of graph is seen. CFRP also increases the stiffness of the column.

4.2.3 Control Specimen Vs CFRP Wrapped Strip Column

Table 4:2: Ultimate load and Ductility data for control and Strip CFRP wrapped column

Specimen	Ultimate load (KN)	Increase in Load %	Displacement(mm)	Increase in Ductility (mm) %
CS	282		8.66	
CWSC	507	79.78	43.66	404.15

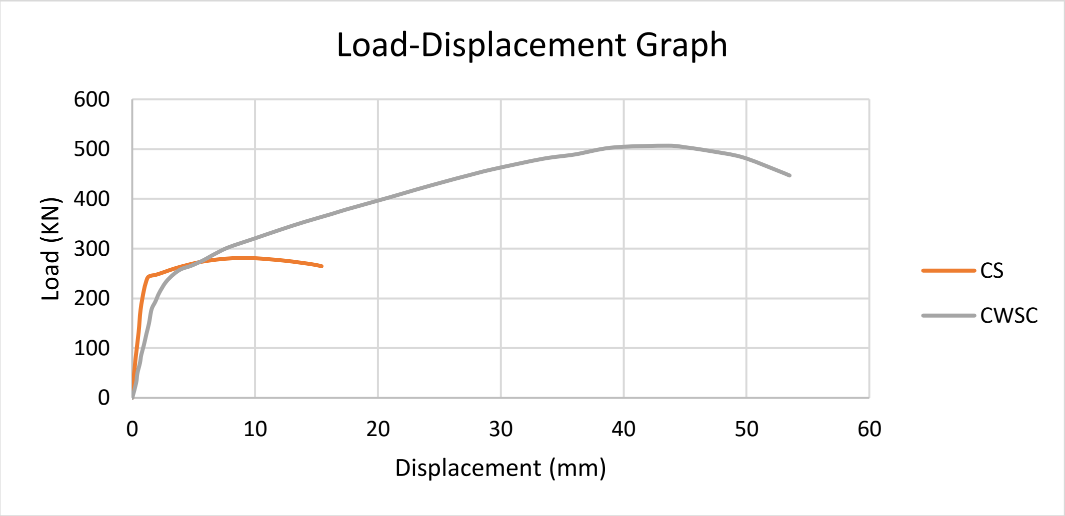


Figure 4:3 Load vs Displacement graph between Control Column and Strip CFRP wrapped Column

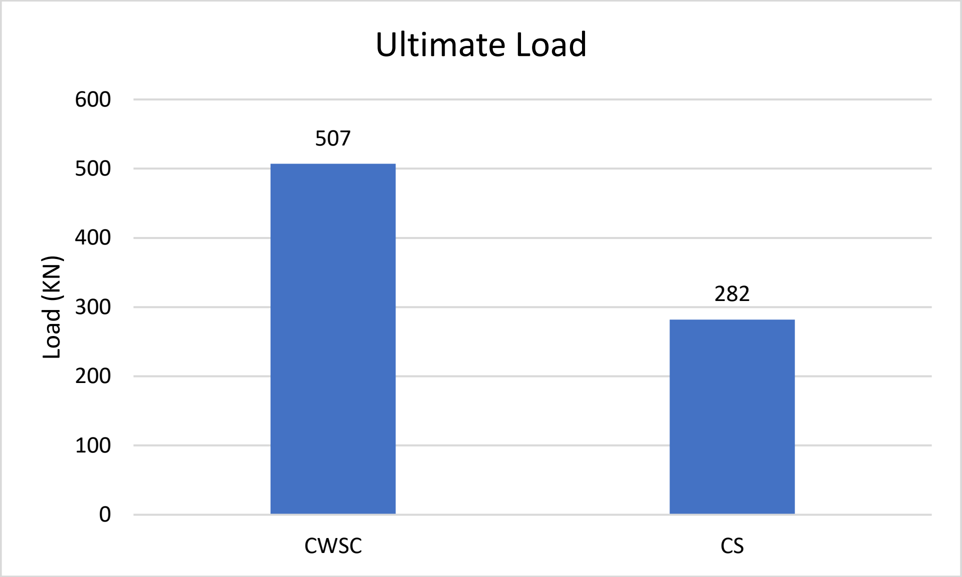


Figure 4:4 Ultimate load-carrying capacities of control and Strip CFRP wrapped column.

4.2.4 Discussion

From the result, it is clear that CWSC has more load resistance than CB. Load resistance of CWSC has increased up-to 79% than CB and displacement increased up-to 404%. For CB, after the yielding of the reinforcement an ultimate peak value of load is noticed and after that ultimate failure of the column occurs. But for CWSC after the linear increase of load instead of yielding reinforcement CFRP start carrying load and an increase of graph is seen. CFRP also increases the stiffness of the column.

4.2.5 Summary

Table 4:3 Summary table of Ultimate load and Ductility data for control, fully wrapped and strip wrapped columns.

Specimen	**Ultimate load (KN)**	**Increase in Load %**	**Displacement(mm)**	**Increase in Ductility (mm) %**
CB	282		8.66	
FCWC	787	179.08	54.13	525.06
CWSC	507	79.78	43.66	404.15

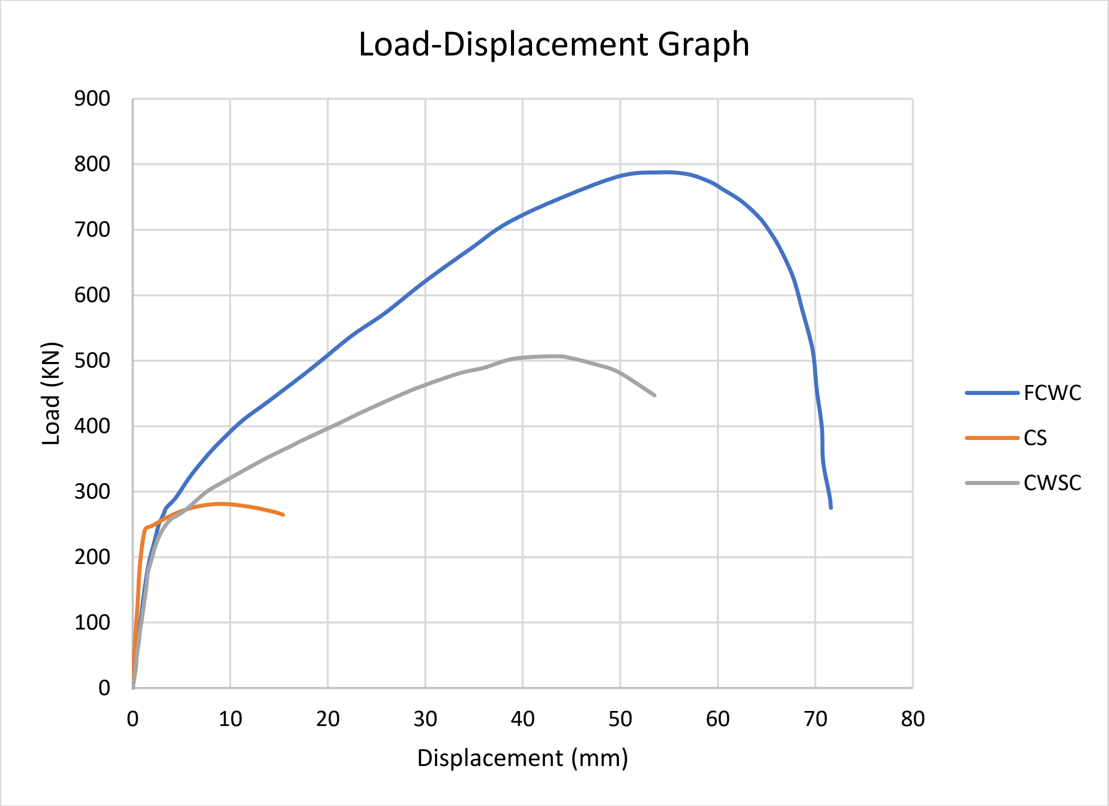


Figure 4:5 Ultimate load-carrying capacities of control and Strip CFRP wrapped column.

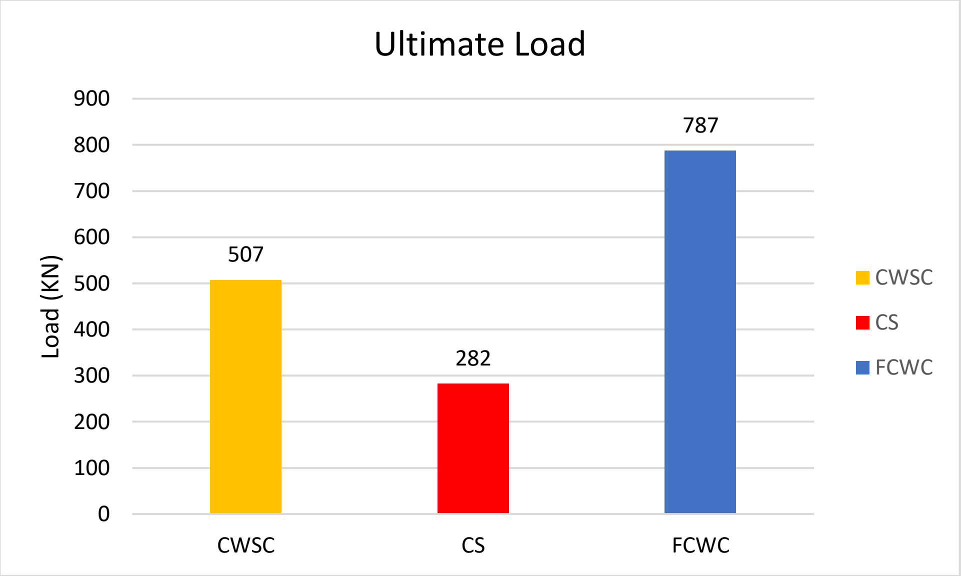


Figure 4:6 Ultimate load of all columns

4.2.6 Discussion

From the summary table, it is clear that FCWC has more load resistance than CS. Load resistance of FCWC has increased up-to 193% than CS and Ductility increased up-to 525%. For CS, after the yielding of the reinforcement an ultimate peak value of load is noticed and after that ultimate failure of the column occurs. But for FCWC after the linear increase of load instead of yielding reinforcement CFRP start carrying load and a high increase of graph is seen. CFRP also increases the stiffness of the column.

It is clear that CWSC has more load resistance than CB. Load resistance of CWSC has increased up-to 79% than CB and displacement increased up-to 404%. For CB, after the yielding of the reinforcement an ultimate peak value of load is noticed and after that ultimate failure of the column occurs. But for CWSC after the linear increase of load instead of yielding reinforcement CFRP start carrying load and an increase of graph is seen. CFRP also increases the stiffness of the column.

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.

If only an isolated portion of the column is accessible, a compression crack may appear similar to a tensile crack.

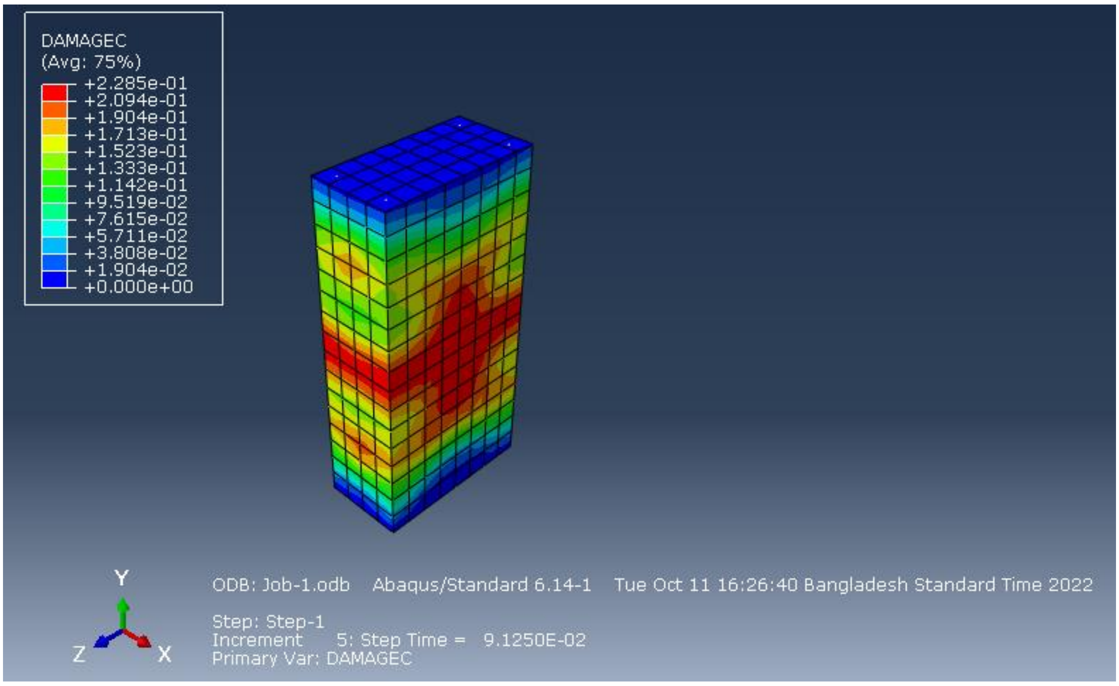


Figure 4:7 Compression cracks of column

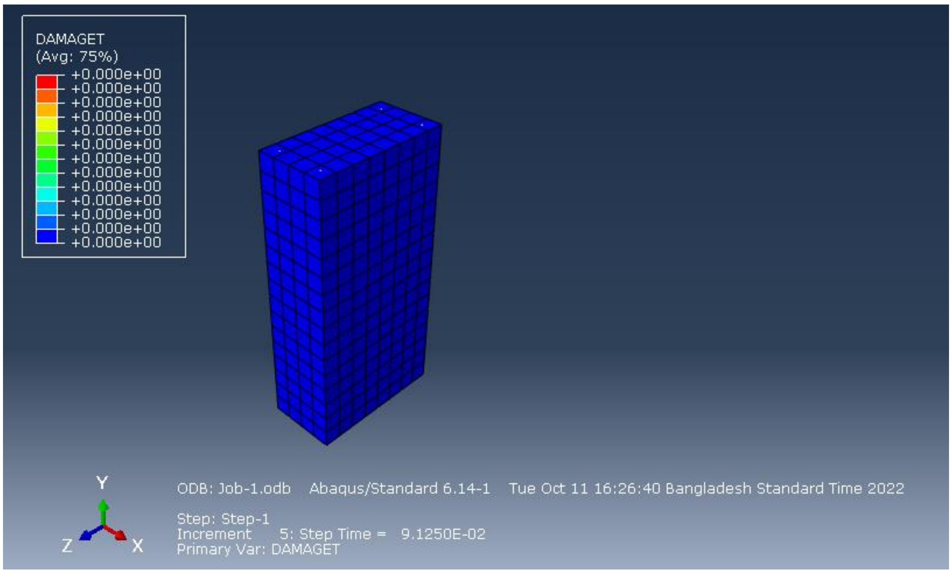


Figure 4:8 Tensile cracks of column

4.4 Discussion

After inspecting all the cracks, it is seen that all the cracks create with respect to principal stress direction. This clearly indicated that these cracks are compression 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.

(Anik & Nur, 2021) experimented this same setup which is analyzed in this Study. From the experiment they have found out that normal reinforced concrete column can resist up-to 268 KN compressive load and from the FE analysis it is seen that CS take up-to 287 kN load.

Table 4:4 Error percentage between Experimental and FE analyzed column

Program	**Ultimate Load(kN)**	**Error (%)**
Experiment Column	268	
FE analyzed Column	282	7.09

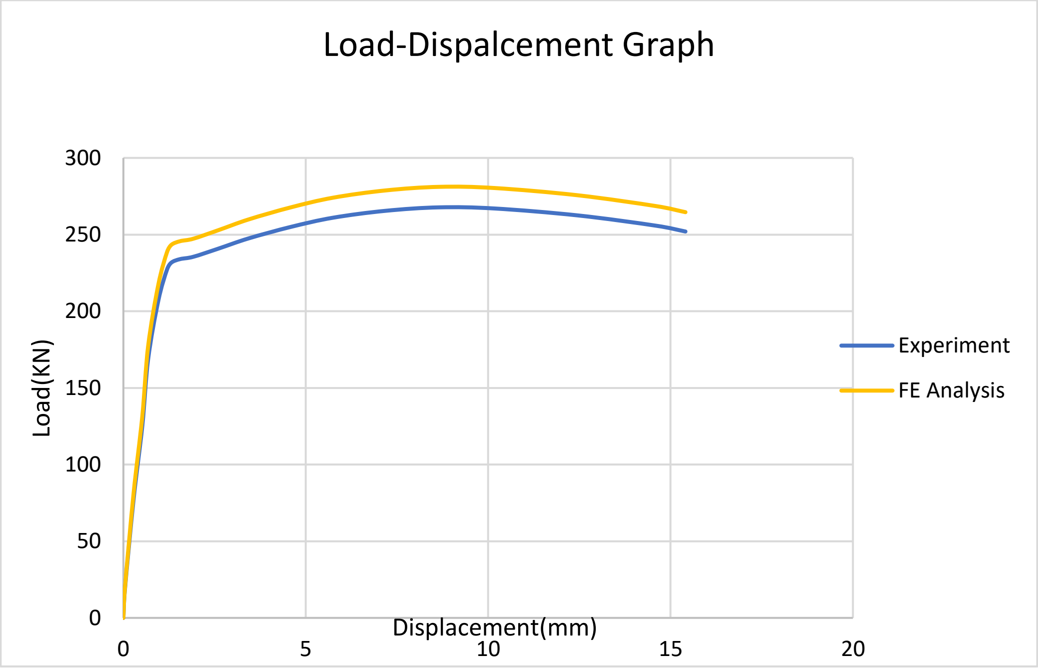


Figure 4:9 Load vs Displacement of Exp and FE analysis

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 load vs Displacement graph has been plotted. All the FRP wrapped column graphs are compared with the Control column graph and significant improvement has been noticed. The ultimate load-carrying capacities of all the columns are also determined. Based on the finite element result and experimental work following conclusion are drawn:

- The ultimate load of all strengthen columns were greater than the control columns.
- The increase in magnitude depends on the FRP strengthening configurations.
- The maximum increase in load is obtained for fully CFRP wrapped configurations.
- Fully CFRP wrapped column increased load resistance up-to 179 % than control column.
- CFRP wrapped strip column increased the displacement which is 404.06%.
- The maximum increase in displacement was observed by Fully CFRP wrapped column with is up-to 525.14%
- Compared to the Experimental work and FE analyzed result, the error is only 7.09%.

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 giving the more accurate results.

The following working scopes can be researched in the future:

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

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