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**NUMERICAL MODELING OF RC DEEP BEAMS
STRENGTHENED BY FRP IN ABAQUS**

Master of Science

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NUMERICAL MODELING OF RC DEEP BEAMS STRENGTHENED BY FRP IN ABAQUS

by

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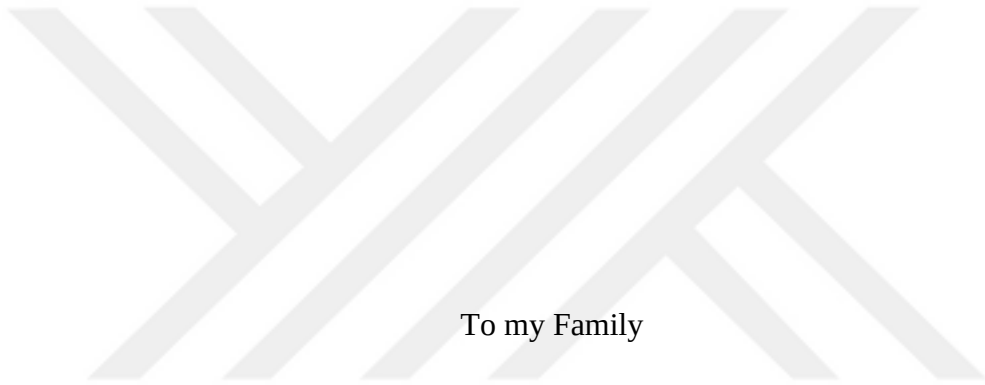
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Hawraa Dheaaldin Abdulkarem Al-hashimi

Signature

DEDICATION



To my Family

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ABSTRACT

NUMERICAL MODELING OF RC DEEP BEAMS STRENGTHENED BY FRP IN ABAQUS

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Although in the last two decades the Fiber Reinforced Polymer (FRP) has been widely considered as an applicable material to strengthen and rehabilitation of reinforced concrete beams, there are a lack of investigation about the effect of this method on the strengthening of the reinforcement beams with web openings. However, some experimental and numerical investigations have been established to analyze the influences of these materials, but further comprehensive studies need to be done. In the current thesis the effect of FRP laminates as a strengthening additive on Reinforced Concrete (RC) deep beams with opening have been investigated. Furthermore, the flexural behavior of RC deep beams with opening strengthened by FRP, and RC deep beams without opening have been studied using ABAQUS Finite Element Method (FEM) software. To this end, one reinforced concrete deep beam specimen was used as control beam, and two RC deep beam specimens with circular and square openings without any further strengthening and two RC deep beams with circular and square opening strengthened by FRP were analyzed. The results of numerical analysis and simulations confirmed the positive influence of the fiber reinforced polymer (FRP) laminates as the strengthening additive on RC Deep beams with opening.

Keywords: Deep Beams, Reinforced Concrete, ABAQUS, Finite Element method, Fiber Reinforced Polymer

TABLE OF CONTENTS

	<u>Pages</u>
ABSTRACT.....	vii
LIST OF TABLES	x
LIST OF FIGURES	xi
1. INTRODUCTION	1
1.1 DEEP BEAMS	2
1.1.1 Deep Beams With Web Openings	3
1.1.1.1 Parameters Of Deep Reinforced Concrete Beams With Web Openings	3
1.2 BRIEF INTRODUCTION FOR STUDY	3
1.3 PURPOSE.....	4
1.4 FIELD, DATA SOURCES, LOCATION-TIME, AND SUPPORT	5
1.4.1 Method And Technique	5
1.4.2 Finite Element Model (FEM)	5
2. LITERATURE REVIEW	6
2.1 CONCRETE	17
2.1.1 Compressive Behavior Of Concrete	17
2.1.2 Concrete Confinement	18
2.1.3 Kent And Park’s Stress-Strain Model	19
2.2 POISSON RATIO	20
2.2.1 Poisson Ratio for Concretes	21
2.2.2 Conditions For Calculating The Poisson Ratio	22
2.3 REINFORCED CONCRETE WITH STEEL	22
2.4 FIBER REINFORCED POLYMER (FRP).....	24
2.4.1 Fiber	26
2.4.2 Matrix	26
2.4.3 Benefits of using FRP	27

2.4.4	Disadvantages of FRP	28
2.4.5	Basalt Fiber-Reinforced Polymer (BFRP).....	29
2.5	DEEP REINFORCED CONCRETE BEAMS	29
2.5.1	Deep Reinforced Concrete Beam With Opening	30
2.5.2	Reinforcement of Deep Beam of Reinforced Concrete with Opening.....	30
3.	METHODS AND SIMULATION.....	32
3.1	PART MODULE.....	33
3.2	PROPERTY MODULE.....	35
3.3	ASSEMBLY MODULE.....	38
3.4	STEP AND INTERACTION MODULES.....	39
3.5	LOAD MODULE	40
3.6	MESH MODULE.....	41
4.	RESULTS AND DISCUSSION.....	43
4.1	REINFORCED CONCRETE BEAM WITHOUT WEB OPENING	45
4.2	REINFORCED CONCRETE BEAM WITH CIRCULAR WEB OPENING	50
4.3	REINFORCED CONCRETE BEAM WITH RECTANGULAR WEB OPENING.....	54
5.	CONCLUSIONS.....	60
6.	RECOMMENDATIONS FOR FUTURE WORKS.....	61
7.	REFERENCES	62

LIST OF TABLES

	<u>Pages</u>
Table 4.1: Properties of the material used for failure modeling.	43
Table 4.2: The name and related abbreviation of the models.	44
Table 4.3: The results of Max. von Mises stress for each condition with their abbreviations.	58



LIST OF FIGURES

	<u>Pages</u>
Figure 1.1: Seismic Hazard Map in the Globe and Turkey	1
Figure 2.1: Diagram of a stress-strain type of concrete under uniaxial load	18
Figure 2.2: Concrete Confinement.....	19
Figure 2.3: The main and modified curves of confined concrete	20
Figure 2.4: Analytical Stress–Strain Relationship for Concrete Confined by Steel Stirrups.	23
Figure 2.5: FRP Schematic Demonstration	24
Figure 2.6: FRP Profile Schematic Representation	25
Figure 3.1: Schematic of system design and four-point flexural test	33
Figure 3.2: Part module environment and created parts.	34
Figure 3.3: BFRP model created in part module of the ABAQUS.....	35
Figure 3.4: Property module of ABAQUS.	36
Figure 3.5: Material properties of BFRP.	37
Figure 3.6: Elastic mechanical behavior of BFRP.....	37
Figure 3.7: Assembly module of ABAQUS.	38
Figure 3.8: Assembly of the four point bending test simulated in ABAQUS.	38
Figure 3.9: Embedded region inside the concrete beam.	39

Figure 3.10: The step and interaction parts of ABAQUS.	40
Figure 3.11: The location of the loadings and supports on the beam.	41
Figure 3.12: Mesh of the beam and setup.	42
Figure 3.13: Meshed BFRP.....	42
Figure 4.1: Compressive behavior of concrete employed in this simulation.....	43
Figure 4.2: Tensile behavior of concrete used in this simulation.	44
Figure 4.3: Stress distribution on the RCBeam.	45
Figure 4.4: Stress distribution on the RCBeam-BFRP-Wrapped.	45
Figure 4.5: Strain magnitude on the beam after loading.....	46
Figure 4.6: Stress distribution on the BFRP-Wrapped individually.	47
Figure 4.7: Stress distribution on the BFRP-Wrapped individually from the bottom view.	47
Figure 4.8: Stress distribution bars and stirrups of the embedded region inside of the beam.	48
Figure 4.9: Yielding criteria of the RC beam under the flexural bending without BFRP	49
Figure 4.10: Yielding criteria of the RC beam with BFRP layer under the flexural bending. ...	49
Figure 4.11: Stress distribution on the RCBeam-C.	50
Figure 4.12: Stress distribution on the RCBeam-C-BFRP-Wrapped.	50
Figure 4.13: Strain magnitude on the system after loading.	51

Figure 4.14: Stress distribution on the BFRP-Wrapped with circular web opening individually.	52
Figure 4.15: Stress distribution on the BFRP circular web opening individually .	52
Figure 4.16: Yielding criteria of the RCBeam-C under the flexural bending without BFRP	53
Figure 4.17: Yielding criteria of the RCBeam-C-BFRP-Wrapped layer	53
Figure 4.18: Strain magnitude on the beam after loading.	54
Figure 4.19: Stress distribution on the RCBeam-R-BFRP-Wrapped..	55
Figure 4.20: Stress distribution on the BFRP-Wrapped with rectangular web	56
Figure 4.21: Stress distribution on the BFRP-Wrapped with rectangular web opening	56
Figure 4.22: Yielding criteria of the RCBeam with rectangular web opening without BFRP.	57
Figure 4.23: Yielding RCBeam with rectangular and with wrapped BFRP layer	57
Figure 4.24: Maximum von Mises stress on the concrete beam in different cases.	59

1. INTRODUCTION

Earthquake is the significant parameters in structural civil engineering. Figure 1.1 demonstrates the seismic hazard map in turkey [1]. In this regard, one of the plans of governments and people to reduce the risk of earthquakes is the plan to study and implement the rehabilitation of important government buildings, infrastructure, and vital arteries of the country. Success in seismic retrofitting as part of seismic remediation depends on utilizing new retrofitting techniques and skills. Among these innovations, polymer-reinforced fibers have a special place.

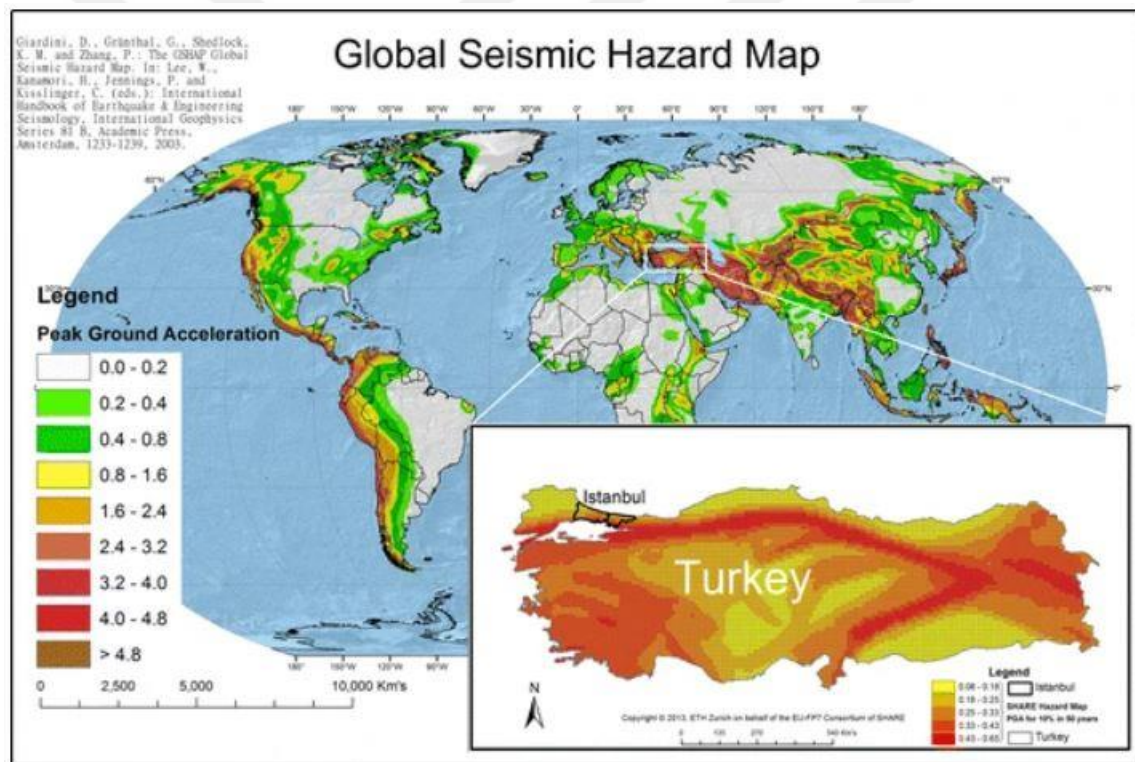


Figure 1.1. Seismic Hazard Map in the Globe and Turkey [1].

Among these, deep reinforced concrete beams are widely used in high-rise buildings, tanks, rectangular silos, floor diaphragms, shear walls, slabs and transfer beams in marine structures and foundations, underground shelter walls and also in load-bearing walls. Buildings etc. have been used. Existence of many openings in such beams is essential to create access, for instance doors and windows or to pass the main facilities such as ventilation pipes, water, electricity, sewage, air conditioners, etc.

Otherwise, the behavior of reinforced concrete structural members during loading is very important to improve the safety and performance of the structure. Various methods have been used to obtain the response of structural members so far. Laboratory studies have been widely used as a method for analyzing structural elements. Although this method gives results that are largely consistent with the facts, it is very time consuming and costly. Using the finite element analysis method to study structural members is another method that is used today. In the past, early studies in this area were time consuming due to poor hardware and software facilities. However, in the last decades, the usage of FEM analysis has expanded due to the advancement of knowledge and increasing hardware and software capacity. Using computer software to model the aforementioned elements is very cheaper and faster.

The data gathered from a FEM analysis will not be beneficial without understanding and applying the necessary steps and also knowing that what is going on inside the created software model. Necessary controls should also be performed at key points to ensure software output.

1.1 DEEP BEAMS

A deep beam is a beam whose depth is comparable to its length. Some reinforced concrete beams are taller than usual compared to their spans. In these beams, external forces and abutment reactions are located on the member plate and a state of plate tension is created in the concrete. Such beams are called deep beams [2-6].

Due to their high height, these beams have a high stiffness, and in structures where the beams have to transmit a lot of force to the columns - and the construction of ordinary beams is uneconomical for example in tall buildings, piers, bridges, silos, dams and foundations. Box beams are used. The type of failure of these beams is generally shear, but there is a possibility of fracture of flexural, shear, buckling and local type, but generally the study of behavior is related to the rupture of the shear type. The high height-to-span ratio in these beams means that the linear behavior - assumed for ordinary beams - is not true in these beams and their behavior is studied nonlinearly, and in general they have fundamental differences with ordinary beams. In order to fill the gap of information about the behavior of these beams, a lot of research has been done and is ongoing.

1.1.1 Deep Beams with Web Openings

Often, in order to facilitate the performance of basic services such as ducts, air ducts, access to electrical and computer cables, mechanical installations or even travel from room to room, openings are made in the deep beams of reinforced concrete [7-10] .

1.1.1.1 Parameters related to the behavior of deep reinforced concrete beams with web openings

- a) Aperture to depth ratio
- b) Beam cross section (rectangular cross section, T-shaped, etc.)
- c) Position and percentage of longitudinal reinforcement
- d) Amount and type of John reinforcement
- e) Mechanical and structural behavior of concrete and steel
- f) Ratio of net cutting opening to beam depth
- g) Type of load and its location
- h) Size, shape, opening place and etc.

1.2 BRIEF INTRODUCTION FOR STUDY

Reinforced concrete deep beams are commonly utilized in high-rise buildings, offshore and coastal structures, transmission beams, various walls, as well as piles. The existence of web openings in the beam core in some deep beams is inevitable due to access such as doors and windows, or due to installation and architectural needs, or due to changes in the use of the building, which reduces the capacity of the member, so Several safe solutions must be provided for the risk of such a weakness. To date, limited studies on the behavior and strength of aerated reinforced concrete deep beams have been reported in the literature. The conclusion obtained from these studies is that the presence of opening causes a significant reduction in the resistance

of deep beams of reinforced concrete. In cases where the presence of such openings is unavoidable, appropriate solutions must be provided to enhance the strength of the beam and compensate for the reduction in resistance. There are various methods for repairing and reinforcing deep beams. The use of composite polymer fibers known as FRP in reinforcing ordinary reinforced concrete beams has been widely studied by researchers. The results of this research show the significant impact of the use of FRP sheets in There has been an increase in the strength of reinforced concrete beams. Despite extensive research on shallow reinforced concrete beams, little research has been conducted on reinforcing deep reinforced concrete beams. In this regard, various theories of researchers on the effect or not of FRP sheets in increasing the final strength of deep beams have been expressed.

1.3 PURPOSE

The main purpose of this study was to examine the nonlinear and numerical analysis of deep reinforced concrete beams with BFRP-reinforced openings. In this study, the four pint bending test was modeled and studied, and for the modeling and accurate numerical study, strong Abaqus finite element software was used [11].

In the current work, after reviewing the types of linear and nonlinear analyzes and determining the strengths and weaknesses of each of the analytical methods, advanced methods of nonlinear static analysis are examined.

In this study, using the method of finite non-linear components, 5 samples of deep beams with simple supports under concentrated load, modeling and BFRP efficiency on the final resistance of deep beams of reinforced concrete with openings have been studied. For this purpose, a sample of deep reinforced concrete beam without opening as a control beam, 2 deep beams of reinforced concrete with circular and square opening without reinforcement and 2 samples of deep beam of reinforced concrete with circular and square opening reinforced with BFRP sheets to U-shaped face is used. In this study, the openable samples are loaded to the failure level and the effect of increasing the resistance in deep openable beams reinforced by BFRP is investigated.

In these samples, a steel plate with dimensions of $10 \times 50 \times 150$ mm at the top of the sample was used at the place of load application and two steel sheets with dimensions of $10 \times 50 \times 150$ at the lower two ends of the sample were used to apply the support load.

1.4 FIELD, DATA SOURCES, LOCATION-TIME, AND SUPPORT

We are going to use numerical and analytical modeling and calculation to compare the strength of raw reinforced concrete deep beam versus reinforced concrete deep beam with strengthened by fiber reinforced polymer laminates.

1.4.1 METHOD AND TECHNIQUE

Using ABAQUS Finite Element Method to get required results. ABAQUS CAE is one of the most commonly used software which is very suitable for solving the problems using FEM. Furthermore, this software is very user friend, and the modeling and analysis can be done using ABAQUS. The ABAQUS includes 5 different main software and ABAQUS/CAE, is abbreviation of "Complete ABAQUS Environment".

1.4.2 Finite Element Model (FEM)

The ABAQUS/Explicit software has a advanced failure models for different types of materials such as metals, plastics, and composites that can be utilize for modeling impact. One of the aforementioned failure models is Hashin's damage model which can be used for cooperation of the elements by applying a continuum shell element.

2. LITERATURE REVIEW

The use of various methods of reinforcement and safety is very common due to the shortcomings in the design and implementation of structures. One of the methods that has been considered in the last few years is the repair and strengthening of weak and damaged members of reinforced concrete with fibrous sheets.

It is a composite polymer. The use of these materials has several advantages, such as increasing corrosion resistance, improving mechanical and load-bearing characteristics, lightness, and ease of implementation. Reinforced concrete beam improves its bearing capacity by gluing FRP sheets to the beam tensile side.

Although much is known about the performance of FRP sheets and their short-term behavior, little is known about their long-term behavior and durability in contact with concrete. In particular, the performance of reinforced components in repetitive loading must be known so that they can be used to reinforce bridges and parking structures that are subject to repetitive loading of vehicles.

Records of studies in the field of beams reinforced with FRP sheets in static and repetitive loadings show that: Many tests have been done on the performance of components reinforced with FRP sheets in static loads. Some of these experiments were performed by Trentfillo [11] in 1998, Chajes [12] in 1995, and Ross 1999 [13] on reinforced beams in bending. In all of the above cases, the researchers' experimental results indicate an increase in the strength of the beams. In 2000, Mahmoud Mahilmi et al. presented a method of analysis of flexural beams using force balance relationships and strain compatibility in cross-sections in different states and compared their method with the experimental results of other researchers and concluded that the difference between theoretical and laboratory results on average, it is only 9.6%. In some of these experiments, to investigate the increase in flexural capability and properties of beams, 16 concrete beams were made and tested using different composite layers (single, three-layer and five-layer), and the increase in flexural strength was quite evident.

Most tests performed on beams reinforced with FRP sheets under repeated loading have been performed on small beams. In 1999, Ross et al. [13] tested CFRP-reinforced beams under fatigue

load and published their results. This study showed that FRP sheet can withstand more cycles after rupture of longitudinal reinforcement. In 1999, Shahvi et al. [14] conducted experiments on concrete beams reinforced with CFRP sheets in static loads and fatigue, and static test variables included the strength of concrete, the number of reinforcing layers with CFRP sheets, and the position of the sheets. Fatigue test was performed on beams with different number of FRP layers, and an unreinforced beam was first loaded with fatigue until the middle of its life, and after reinforcement, they continued to load with fatigue. CFRP sheet reinforcement increases the fatigue life, stiffness and flexural capacity of beams. In 2001, Christos et al. [15] conducted a study to investigate the effect of GFRP sheet reinforcement on the fatigue strength of reinforced concrete beams. On unreinforced concrete beams and reinforced with GFRP layers. The results of research show that at similar repetitive loading, the fatigue life of reinforced concrete beams reinforced with GFRP sheets was longer than the fatigue life of unreinforced beams. Interestingly, although GFRP sheets increase the fatigue life of beams, the fatigue degradation mechanism is the same in reinforced and non-reinforced beams, and in both, rupture occurs after rupture of longitudinal rebars due to fatigue. As a result, using the existing fatigue models, the fatigue life of reinforced beams in repetitive loading can be predicted.

Evaluating the research conducted in the country and in order to continue scientific and research programs, a laboratory program was developed to study the fatigue strength and behavior of reinforced concrete elements reinforced with GFRP sheets.

Compression of 32.6 MPa and series one rebars and in the second group, concrete with 9.45 resistance and series two rebars are used. The beams were shear-reinforced in such a way that they were broken in the bending position.

The specifications of concrete and steel rebars are given in Tables 1 and 2. Each group of eight consists of four binary subgroups and each of the subgroups were: - Control samples: without reinforcement - Reinforced samples: with one, two and three reinforcement layers of two beams in each sub-A double group, one beam is loaded in static mode and the other beam is loaded repeatedly. Details of beam reinforcement are given in Figure 1. Composite sheets were made of glass fibers 600 g / m² and epoxy resin with a modulus of elasticity of 9.278 MPa and tensile strength of 6.7 MPa. Composite sheets were glued to the beams with the help of epoxy adhesive with modulus of elasticity of 4300 MPa, shear strength of 30 MPa and tensile strength of MPa

(15-20). Table 3 shows the mechanical specifications of beam reinforcement sheets.) The coding of the beam model is done as follows. The letter F represents the flexural tests, the letter L, and the letter L represents the number of FRP reinforcement layers. For example, F-1L-33-C represents a beam made with a compressive strength of 33 MPa concrete reinforced with a layer of FRP and loaded repeatedly.

A review of past studies and research shows that early research was often based on the elastic behavior of deep beams. Of course, today elastic studies can be easily done using finite difference techniques and finite elements. But an important drawback of elastic studies is the use of the usual assumption that Hooke's law governs isotropic materials, so these studies do not help us well for design purposes.

Ramana et al. [16] conducted an investigation on the effect of different reinforcement degrees on the structural behavior of CFRPC-reinforced concrete beams. In this study, laboratory outcomes and analytical findings of flexural reinforcement of RCBs by external bonding of high-strength and lightweight CFRP sheets in the tensile zone of the beam have been investigated. In this experiment, 4 beam samples, 3 beam samples with different amounts of CFRPC reinforcement by changing the width of the sheets and one beam sample without reinforcement with CFRPC by 4-point loading method in the 900 mm cutting hole have been studied. In this study, the largest increase in the crack initiation stage and final anchors is about 150 to 230%. In this study, the increase in hardness of reinforced beams is significant and is about 110%.

In 2016 Al-Osta et al. [17] investigated two distinct methods to improve the strength of RC beams both utilizing ultra-high performance fiber reinforced concrete (UHPFRC). The first method is the well-known sandblasting technique during which the exterior surfaces of the reinforced beams were sandblasted and subsequently cast by UHPFRC. The second method was simply covering the beam with UHPFRC layers. Also, they used three distinct composition configurations; the first type of samples had a UHPFRC layer only on one bottom side, the second type had two of their longitudinal sides improved, and eventually, the third group had three different sides covered with UHPFRC layers. Several flexural characteristics of the reinforced beams such as stiffness, yielding stress, and crack propagation were examined. A notable improvement was observed in all strength-related properties of each and every single sample. As it was expected the samples with reinforcement layer on their 3 sides displayed the

maximum improvement. Nevertheless, the ductility of the beams had an inverse relation with the increment of UHPFRC layers meaning that even though UHPFRC layers increased the tensile strength of the beams, they could cause a reduction in the eventual ductility of the beams. They reported that the results of their numerical Finite element (FE) analysis were in complete agreement with the experimental results.

Kara and Ashour [18] investigated the moment capacity, curvature, and deflection of the Fibre-reinforced Plastic (FRP) RC beams numerically. They utilized numerical methods in calculating the force equilibrium and strain compatibility equations as the concrete does not show the proper linear behavior. They used flexural rigidity and deflection relations to calculate deflection analytically. The state-of-the-art process in this work was the introduction of modification in the calculation of the mid-span rigidity as the existing method could not explain the observations properly. They reported that their models have successfully explained the existing experimental data and they are in complete agreement with the experimental results of the FRP RC beams. The existing ACI-440.1R-06 relations had not taken into account the importance of deflection properly, so the introduced modifications that were composed of relations with an additional correction factor considering the beam's flexural rigidity solved the deviations in the analytical analysis of deflections of continuous RC beams relative to the experimental results.

H. Toutanji et al. [19] reported the effective impacts of external FRP layers on the strength of RC beams that are going under flexural charges. They installed the FRP layers on the surface of RC beams using an inorganic material such as epoxy resins. Their experiment was consisting of eight RC beams, among which there was one control beam, and seven other specimens improved by several layers of CFRP strips. They exposed all the samples to a four-point bending exam and studied the deflection, midspan strain, and failure mode. They reported up to 170.2% improvement in the tensile strength of the CFRP reinforced beams relative to the control beam. They also demonstrated that the strength increases by the number of CFRP layers. The failure mode for the beams with three and four strips of CFRP was rupture but for the beams with five and six layers the failure mode was delamination. Nevertheless, this team also has observed a reduction in ductility of the CFRP reinforced beams relative to the control beam.

Osman et al. [20] studied the influence of openings on the shear strength of RC beams. The study was conducted with a total number of 31 RC beam samples none of which carrying any

additional shear reinforcement. Osman et al. approached this problem with both experimental and numerical techniques, the numerical analysis being the Finite element method (FEM). Also, they have studied circular openings in particular. They reported a decrease in all structural characteristics of the beam for which they believe the stress concentration about the opening was responsible. They studied several parameters among which the opening location, size, and the shear span-to-depth ratio were most important. They utilized ANSYS FEM modeling to study these properties and they studied 3 RC beams without openings and one beam with opening experimentally under two-point loading to have a firm basis for validating the FEM results. The FEM models indicated that the opening located higher on the beam decreased the strength more prominently and the failure was much faster. The state-of-the-art procedure in this paper was the introduction of an analytical relation for shear strength of this kind of RC beams. Also, the FEM models used in this study were flexible to be utilized and developed for beams with a different number of openings and distinct shapes of openings.

Mansur et al. [21] conducted studies on "Shear reinforcement of reinforced concrete beams via reliable external FRP methods" in which 6 deep concrete beams were fabricated and tested to the point of rupture. One of these beams was tested according to its initial condition and without reinforcement to be used as a reference. The rest of the samples were tested by tape and string after wrapping CFRP sheets. Experiments have demonstrated that the utilization of reliable FRP reduces the growth of critical diameter cracks and also increases the bearing capacity of the beam.

Obaidat et al. [22] investigated the "improvement of reinforced concrete beams using composite sheets". This study shows the results of a laboratory study to investigate the structural behavior of fully damaged reinforced concrete beams improved by CFRP sheets in the shear zone or in the flexural zone. The use of CFRP sheets by external gluing method increases the maximum load. The maximum load increase of the improved specimens is about 23% for shear reinforcement and between 7-33% for flexural reinforcement. Also, reinforcement changes the failure mode to brittle failure. On the other hand, strengthening the beams reduces the crack width compared to the control beam. Laboratory results show that increasing the length of CFRP sheets in the flexural area increases the repair efficiency and increases the strength of concrete. The results of

this study show that the main failure mode is the separation of CFRP sheet from the concrete surface, which reduces the reinforcement effect.

Murali et al. [23] investigated the "reinforced concrete beam model with FRP reinforcement externally". This research study evaluates the structural behavior of reinforced concrete beams with FRP reinforcements by external bonding method. In this study, 3 different steel ratios with 2 different types of GFRP and 2 types of thickness in each type of GFRP were used and a total of 15 beam samples were used. A 3 m long rectangle was constructed for this study. 3 beam samples were used as control beams and the rest of the samples were reinforced using GFRP sheets. The results of this study show that beams reinforced with GFRP panels show better performance. Flexural strength and ductility increase significantly with the increasing depth of GFRP sheets. The primary crack load for 5 mm WRGFRP sheets was increased by more than 88.89%, yet this quantity was measured to be about 100% for 3mm sheets of WRGFRP. The increase in ductility in beams reinforced with 5 mm WRGFRP sheets is about 56.01 percent and 64.69 percent. The GFRP sheets were more susceptible to the deformations under the tensile stress caused by primary crack loads, nevertheless, the reduction of primary crack loads was as high as 50.59 % and 58.59 for 3mm sheets and 5mm sheets, respectively. The deformations caused by the first cracks in the tensile region of the beams are much higher for GFRP sheets and the highest reduction of the initial crack load is more than 50.59% for 3 mm thick sheets and more than 58.59 mm for 5 mm thick sheets. Surrender loads are significantly increased due to the adhesion of GFRP sheets. The increase in surface area obtained by WRGFRP sheets is much greater than that of Chopped Strand Mat GFRP sheets. Increased yield load for CSMGFRP sheets with a thickness of more than 40% and for CSMGFRP with a thickness of 5 mm more than 128.57%, for WRGFRP sheets with a thickness of 3 mm more than 33.33% and for WRGFRP with a thickness of 5 mm more than 200% is. The yield values of GFRP-reinforced beams are much lower compared to control beams, so that the amount of yield reduction deformation for beams reinforced with GFRP sheets with a thickness of 3 mm is between 28.7 - 28.03% and for beams reinforced with GFRP sheets with a thickness of 5 mm are from 5.19% to 28.54%. The rate of final load increase for reinforced beams with CSMGFRP sheets with a thickness of 3 mm is between 28.58-40% and for reinforced beams with CSMGFRP sheets with a thickness of 5 mm is between 28.57-58.57%. Regarding the final load, the beam reinforcement results using WRGFRP are much better compared to CSMGFRP. So that the rate of final

strength increases for beams reinforced with WRGFRP sheets with a thickness of 3 mm is between 43.42 - 33.33% and for beams reinforced with WRGFRP sheets with a thickness of 5 mm between 60 - 200%.

Jahangiri and Khaloo have studied the behavior of RC beams with openings FEM in which the aim was to investigate and evaluate the use of FEM analysis to analyze the behavior of deep reinforced concrete continuous beams. It had an opening in the middle. The shear strength of the beams decreases as the opening size increases. Based on their analysis square openings decrease the shear strength of the beam slightly more than circular ones as the reduction percentages are 20%, and 15%, respectively. However, this difference can be larger or smaller for different cases. This team has reported an increment in the shear strength by turning the square opening to a circular opening between 2 and 13 percent. Also, such a transition could increase the ductility up to 16%.

Park et al. [24] worked on the "pressure-tensile method for CFRP-reinforced deep-reinforced concrete members". The STM method is used to analyze deep reinforced concrete beams with CFRP when the CFRP sheet acts as an additional tensile stress. In this research, using STM method, a practical design and analysis for deep reinforced concrete members reinforced with CFRP sheets is presented. In total, the test results of 17 deep laboratory beams were compared with the results of STM method and it was seen that STM method gives the best agreement with the test results.

El Maaddawy and Sherif [25] conducted a study on "the use of FRP composites in shear reinforcement of deep reinforced concrete beams with opening". This paper presents the results of a research study on evaluating the potential of using external (surface) CFRP sheets as a reinforcement solution to increase the strength of deep reinforced concrete beams with opening. In this study, 13 deep beams with openings were constructed and tested under 4-point loading. The test specimen has two circular openings, each in the shear region, which is symmetrical at both ends of the beam shear opening. Parameters include opening size, position and amount of CFRP sheets. The structural response of deep beams with opening mainly depends on the degree of interruption of the natural load path. The use of external CFRP to strengthen the shear around the openings has been very useful to increase the shear strength of deep reinforced concrete beams. The increase in strength due to the use of CFRP sheets is 35 to 73%. In contrast,

according to the experimental results, an analysis method to predict the shear strength of deep reinforced concrete beams including openings reinforced with CFRP sheets was studied and tested.

N. Dash[26] investigated "Reinforcement of reinforced concrete beams using GFRP". In this laboratory research, the flexural and shear behavior of reinforced concrete beams reinforced with GFRP sheets has been investigated. This test includes 2 groups of reinforced concrete beams, group one includes 3 samples of beams with weakness in bending and group 2 includes 3 samples of beams with weakness in shear. According to the test results and the values of resistance calculated in group one, the initial bending cracks appear in the reinforced beam from below (beam No. 2) in the amount of high loads and the final load bearing capacity in the second beam is 33% higher than the beam. Is the witness (arrow number one). The amount of load in the initial crack increases with the reinforcement of the beam from the area below the beam, such as reinforcement on both sides of the beam, and the final load bearing capacity of the reinforced beam on both sides (beam number 3) is 43% higher than beam number one and 7% higher. It is from arrow number 2. In group 2, the control beam (beam number one), as mentioned earlier, suffered a shear failure due to poor shear. After strengthening the shear area of the beam (beam number 2), with increasing load, the initial cracks appeared in the flexural area of the beam and the cracks moved towards the neutral wire and grew. Finally, as expected, the last failure was flexural failure, which reveals that the GFRP reinforcement improves the shear strength of the beam and the final load bearing capacity of the beam is 31% higher than that of the control beam. However, when the U-beam is reinforced in the shear zone (beam No. 3), the final load bearing capacity of the beam increases by 48% compared to beam number one and 13% compared to beam number two.

Panahi and Arabzadeh performed a study on "Parameters affecting the shear reinforcement of deep reinforced concrete beams using FRP sheets". In this study, the effect of the number of layers and the arrangement of CFRP sheets on the final load capacity and the displacement of the middle of the opening to the applied load of deep reinforced concrete beams that were externally reinforced with CFRP sheets were analyzed. For this purpose, 14 samples including two control samples and 12 amplified samples were included in nonlinear analysis software. The results show that the use of CFRP sheets with a number of layers and different arrangements has

increased the final load by up to 125% in some samples. Based on the outcomes of this work, the cover of the deep beam in the area of the shear spiral in the form of a twist has the greatest increase in the final load capacity. Reinforcement perpendicular to the direction of cracks in the form of strips compared to reinforcement perpendicular to the direction of the cracks in the form of a plate has shown a 19% increase in bearing capacity.

Mohammadhassani et al. [27] conducted a study on "fracture modes and serviceability of self-compacting high-strength deep concrete beams". The main purpose of this study was to simplify the diagnosis and prediction of deep beam failure according to the percentage changes of tensile rebars and life reinforcement. Six deep self-compacting high-strength concrete beams were tested to the point of rupture and failure. Stress was measured on the concrete surface in the middle of the span, tensile rebar and compressive zone of the concrete. The load was applied incrementally and in each load increase, new cracks, crack widths and their propagation path were observed. The results clearly show that, in the finite conditions, the stress distribution on the concrete surface in the middle of the span is not very parabolic. In deep beams, several neutral wires were obtained before reaching the final breaking point. Due to the increase in load, the number of neutral strands decreases and there will be only one neutral strand at the breaking point load. If the longitudinal tensile reinforcement rebars are less than the value recommended by the ACI Code, the deep beam fracture is flexural. Due to the increase in tensile rebar, the rupture in the form of crushed concrete is clearly visible in the nodal areas. The first bending crack in the middle of the opening is always vertical, usually occurring at 25 to 42% of the maximum load. The crack length is about 0.24 to 0.6 times the cross-sectional height. Increasing the percentage of tensile rebar, as it increases the number of cracks, reduces the length and width of the cracks.

Chin et al. [28] studied the "flexural reinforcement of openable reinforced concrete beams with CFRP sheets". This study investigates the reinforcement of reinforced concrete beams with square opening in the flexural zone by CFRP sheets. All 5 specimens were tested to failure under 4-point loading to investigate structural behavior such as crack path, failure mode, final load, and load-displacement diagram. The test outcomes showed that large opening in bending reduces the capacity and stiffness of the beam; And increases deformation and the incidence of cracks. The reinforcement position of each unreinforced beam was designed based on the possible crack

path. Existence of large square opening in reinforced concrete beam, hardness and strength of beam are reduced by 19% and 48%, respectively. Also, in deformation modes, the attendance of a circular opening in the flexural region increases the deformation of the beam by more than 30% compared to a simple beam. The presence of CFRP sheets around large openings in the flexural zone significantly reduces the cracks formed around the openings and also reduces the beam deformation by about 61% in the square opening type.

Alsaq [29] investigated the effects of form and the position of an opening on the mechanical strength of deep Reinforced Concrete (RC) beams with the opening. The study investigates the dependence of the structural behavior of deep RC beams with an opening on the form and position of the opening, not changing the size of the opening. In this study, the finite element method was utilized to execute nonlinear finite element analysis. The ultimate strength obtained from the FEM analysis of the RC deep beam with opening showed less than 20% difference compared to the laboratory results. The main finding of this investigation was that the location of the opening affects the final structural strength much more than its shape, as it may increase the strength up to 100% if it is moved toward the upper corners. Also, the reduction in structural strength reduced by a narrow rectangular opening (with the direction of length in the horizontal direction) is 40% smaller than its value for the large rectangular opening with the same area.

Sayed et al. [30] on "Modeling the shear capacity of reinforced concrete beams reinforced with FRP sheets employing finite element method". Utilizing 3D FEM analysis, the impacts of distinct parameters on the shear strength of deep FRP reinforced beams were studied. The parameters studied are listed as follows: beam width, concrete strength, width to depth ratio of the cut, thickness of the FRP sheets, and reinforcement method (complete twist, U twist, and gluing the sides). A total number of 55 samples were investigated. The results showed that the variables in the analysis cause a secondary strain at the top and bottom of the beams. the shear strength was 18.9%, 17%, and 18.3% for gluing the sides, U-twist, and full twist, respectively.

Jayajothi et al. [31] conducted an investigation on "Finite element analysis of FRP-reinforced concrete beams using ANSYS". In this study, nonlinear finite element analysis has been used to simulate the behavior of fracture states of reinforced concrete beams in the shear and flexural region using FRP sheets. In this study, 4 types of beams have been modeled in ANSYS software, 2 beam samples as control beam without FRP and 2 beam samples by CFRP sheets, the first

reinforced concrete beam as a simple sheet in the tensile area of reinforced concrete beam and the second beam Reinforced concrete is reinforced with U-shaped screws. In this study, the load-deformation relationships up to the moment of failure and the resulting crack paths are compared with the laboratory results in the articles. Load-deformation diagrams acquired from numerical studies are in close agreement with the laboratory results reported by Jeyasehar et al. [32] and Ibrahim et al. [33]. So that if the CFRP sheets are installed correctly in the tensile zone of reinforced concrete beams, the flexural strength of reinforced concrete beams will increase significantly. In this study, the first example of reinforced beam shows between 18 to 20% increase in flexural strength for single layer reinforcement. The load-bearing capacity of the second sample of reinforced concrete beams reinforced using a U-twisted CFRP layer is higher compared to that of the second control beam. The second reinforced concrete beam reinforced with CFRP sheets showed a 76 to 82% increase in flexural strength for single layer reinforcement. In this study, it is shown that numerical solution for calculating and estimating the strength of reinforced concrete beams reinforced with FRP sheets is very simple, cheap and fast in comparison with laboratory calculations. Also, the general modes of finite element models are in close agreement with the observations and information obtained from laboratory studies.

Kachlakev [33] conducted a study on "Finite element analysis and model approval of reinforced concrete beams with shear weakness reinforced with GFRP sheets". In this study, he examined and compared two samples of reinforced concrete beams, one example of reinforced concrete beams without shear rebars and one example of reinforced concrete beams reinforced with GFRP sheets on both sides of the beam. In this study, it is found that the general conditions of finite element models are in close agreement with the observations and information obtained from laboratory samples. Adding GFRP reinforcement to the control beam changes the actual behavior of the beam and model from accidental shear failure near both ends of the beam to flexural failure due to rebar submission in the middle of the span. Shear reinforcement increases the load bearing capacity by 45% for laboratory beams and by 15% for finite element models.

According to the studies and surveys conducted in the area of reinforced concrete deep beams, deep reinforced concrete deep beams, FRP reinforced concrete beams, and FRP reinforced deep concrete beams, it is observed that a large number of Articles and dissertations in these fields have been laboratory and research and numerical studies on these topics are very limited. It is

also noteworthy that in most laboratory studies, only one subject was reinforced concrete beams reinforced with FRP and deep reinforced concrete beams and deep reinforced concrete beams reinforced with FRP and also in some cases several subjects deep reinforced concrete beams. FRP-reinforced deep reinforced concrete beams have been investigated. Also, in some studies, the results obtained from the method used are not accurate and need to be corrected. On the other hand, due to the laboratory nature of many studies in these fields, although largely true, they are very time consuming and costly. Therefore, using the finite element analysis method to study structural members is much more economical, more accurate and faster.

2.1 CONCRETE

Concrete specifications vary depending on the materials used to make concrete, the method of construction and how to enclose it. It is very important to know that concrete is an inelastic, nonlinear and inhomogeneous material that has relatively uniform properties, and to design concrete, these characteristics must be fully known, which are introduced below.

2.1.1 Compressive behavior of concrete

The behavior and performance of a structure depends on the stress-strain diagram of the materials from which the structure is made. Because concrete is commonly used in compression, its compressive strength is important. Therefore, when we talk about concrete strength, we usually mean 28-day uniaxial compressive strength of concrete.

The stress-strain curve of concrete under uniaxial pressure is shown in Figure 2. In this figure it is observed that the deformation of concrete under uniaxial compressive stress is nonlinear; The higher the compressive stress of the concrete, the more obvious its nonlinear behavior becomes. The nonlinear behavior of concrete under compressive stresses is due to the gradual formation of fine cracks in it; So that as the stress increases, the amount of microcracks will also increase.

Strain, such as the maximum stress displayed by, for low-strength concretes to high-strength concretes may vary in the range of 0.0015 to 0.003, although the value for normal-strength

concretes is about 0.002. Taken. The final strain, like the compressive strength of the concrete shown by, will be greater than 0.003 for different types of concrete.

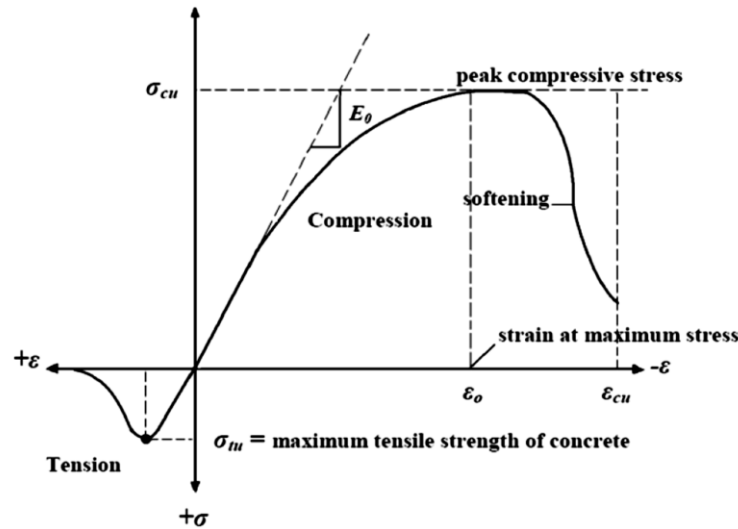


Figure 2.1. Diagram of a stress-strain type of concrete under uniaxial load

2.1.2 Concrete Confinement

In practice, confinement in concrete is usually created by lateral reinforcement, which is either in the form of rectangular braces or spiral braces. The stress-strain relationship of enclosed concrete is quite different from that of non-enclosed condition, and this has been a research topic among researchers for many years. At low stress levels, when the load is applied axially, the lateral reinforcements withstand low stresses and have little effect, because the confinement effect of these reinforcements is passive.



Figure 2.2: Concrete Confinement

The tension in the lateral reinforcements increases with increasing axial load. Concrete The overlay div is responsible for holding dimming the rest of the page. After this point, the concrete inside the side reinforcements acts as a concrete core and begins to expand. While lateral reinforcements prevent this expansion. Therefore, the stresses in the concrete core are no longer uniaxial but occur due to the confinement pressure of the three-axis stress state.

2.1.3 Kent and Park's stress-strain model

Kent and Park introduced the stress-strain model for enclosed concrete in 1971, which consisted of two different parts. The ascending part of the diagram was represented by a parabola (Grade 2) in which the enclosing steel had no role in the maximum stress and strain of the concrete. This assumption meant that Khamut had no role to play until it reached its maximum strain. Maximum stress and strain are the cylindrical compressive strength of concrete. The descending part consists of a straight line that decreases and then moves horizontally with constant tension. The slope of the descending line is determined by two variables.

Kent and Park models were modified in later steps and the effect of lateral confinement in the ascending part of the curve was considered. In the modified Park model, the maximum stress and strain were increased. The descending part of the curve was also corrected, as its starting point was displaced. The model is known as the modified Kent and Park model. Figure 3 shows the model explicitly [23].

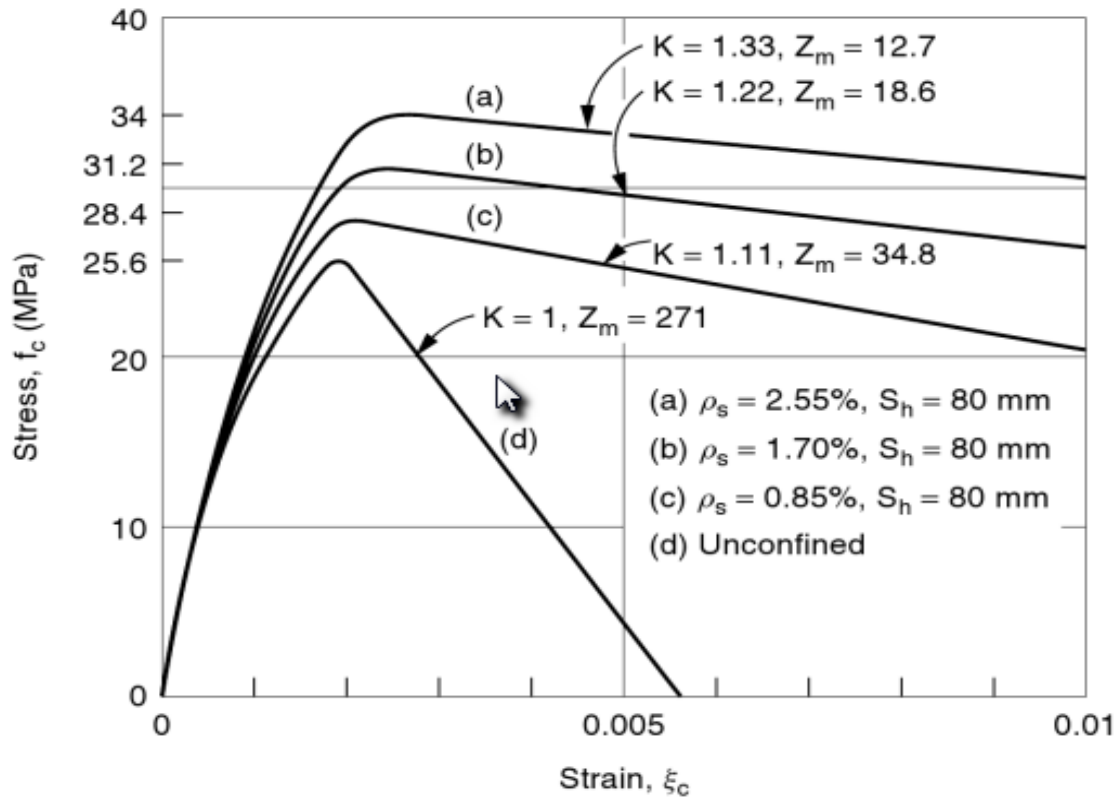


Figure 2.3. The Main and Modified Curves of Confined Concrete

2.2 POISSON RATIO

When a concrete cylindrical specimen is pressed, the specimen increases in lateral direction as the specimen length shortens and axial compressive strains are created. The ratio of lateral strains to axial compressive strains is called the Poisson ratio. Poisson's ratio is usually in the range of 0.1 to 0.3. Based on studies, the Poisson's ratio for concrete can be assumed to be 0.2.

Based on the calculations related to the molecular theory which have been done by Simon Denis Poisson, it is obtained a ratio of $\nu = 1/4$ for isotropic materials. In recent studies based on models based on the atomic structure of materials, a ratio of $\nu = 1/3$ has been obtained for isotropic materials. The Poisson's value for most metals and many other materials is between 0.25 and 0.35. Cork is one of the materials whose Poisson's ratios is very small and practically zero. This ratio is about 0.1 to 0.2 for concrete. The upper limit of the Poisson ratio is theoretically 0.5. The Poisson ratio of rubber materials is close to this value.

As the strain inside a material increases, its Poisson's ratio changes. For example, when plastic surrenders occur in structural steel, its Poisson's ratio reaches about 0.5. Therefore, the Poisson ratio is persistent only in the linear elastic range. If the behavior of the material is nonlinear, the ratio of lateral strain to its axial strain is called the "contraction ratio". In the case of linear elastic behavior, the contraction ratio is equal to the Poisson ratio.

When using Poisson ratio relations, it should be noted that these relations can only be used for bars under uniaxial stress. In uniaxial stress, only the normal stress σ is applied along the axis of the rod.

2.2.1 Poisson Ratio for Concretes

In different concretes, the Poisson's ratio often differs between 0.15 and 0.2. Studies show that there is no consistent relationship between Poisson's ratio and concrete properties, such as water to cement ratio, curing age and aggregate granulation. However, the Poisson's ratio is lower in high-strength concretes, and higher in wet and saturated concretes and dynamically loaded concretes.

- a) The Poisson ratio value of the concrete may vary depending on the form of sample which can be we, dry or saturated and also the loading parameters and conditions.
- b) The Poisson ratio of concrete under the loading with static condition is lower than the ratio of Poisson concrete under dynamic loading.
- c) The ratio of Poisson concrete under dynamic loads is between 0.2 and 0.25.
- d) In general, this ratio varies from 0.1 for high-strength concrete to 0.2 for low-strength concrete.
- e) The most common value for the Poisson ratio in the design of concrete structures is 0.2.
- f) It is recommended that you make sure that the Poisson ratio is consistent with the values employed to determine the elastic shear modulus of the concrete, otherwise you may encounter serious errors.
- g) The ratio of Poisson concrete to 70% strength is a constant value.
- h) Its value can be calculated through the static modulus test.

2.2.2 Conditions for calculating the Poisson ratio

For a specific material, the Poisson ratio persists the same in the linear elastic range. Therefore, as the load increases or decreases, the amount of lateral strain at any point on a prismatic bar changes in proportion to its axial strain. However, other conditions must be met in order for the lateral strains to be constant across the bar when a specific load is applied. In the following, we will explain these conditions.

The first condition for lateral strain uniformity across the rod is the homogeneity of the material. For this purpose, the constituents of the rod must have the same composition in all places and consequently the similar elastic behavior. Nevertheless, the homogeneity of the material in all respects does not mean that its elastic properties are the same in all respects. For example, the modulus of elasticity of materials such as wood in the lateral direction differs from its modulus of elasticity in the axial direction. That is why we go to the second condition.

The second condition for the uniformity of the lateral strain across the rod is the uniformity of the elastic properties of the material in a perpendicular direction to the longitudinal axis. The above conditions apply to most metal materials. For this reason, the lateral strains in metal rods will be the same at all points of the rod under uniform tensile loading. In addition, these strains will be equal in all directions.

Materials that have the same properties in all respects are called "isotropic". If the properties of a substance change in different directions, that substance will be "anisotropic".

2.3 REINFORCED CONCRETE WITH STEEL

Low tensile stress of concrete can cause many limitations in the use of concrete in engineering structures, and this is if the concrete is used alone. Because most concrete members have to withstand shear and bending, these two also create tensile stresses. By adding high-strength ductile reinforcement, concrete can be made into a material that, in addition to high compressive strength, also uses the tensile strength of steel. Of course, there are other ways besides steel to reinforce concrete, such as the use of polymers. Steel can also be used in other forms besides reinforcement to reinforce concrete. Reinforcing concrete with steel not only increases the ductility and hardness of reinforced concrete but also reduces the creep and alluvial effects of

concrete and reduces the width of cracks. In general, there are three ways to express the stress-strain relationship of reinforced concrete. Initially, there is a line segment where a straight line with a slope of the modulus of elasticity of the steel gives the origin a yield stress of f_y , which is approximately 200 GPa. After this stage, the steel enters the hardening part, which continues until the stage of reaching maximum strength.

In this case, which is the elasto-plastic approximation, it avoids increasing the stress in the hardening part and assumes the yield stress of the f_{ye} as the ultimate strength. ACI318-02 [34] also mentions this approximation and suggests its use.

In the three-line approximation, it is assumed that the hardening is linear to the maximum point. The slope of this line is obtained by the linear interpolation method between the maximum stress, which are also determined by the steel test.

In the parabolic approximation, the hardening part is expressed by a parabolic equation (degree 2), which depends on the strain properties of steel in different steel materials. For example, for steel 60 (grade 60 steel), the hardening part is evaluated by the following equation, where the amount of strain is where the hardening begins, and the final strain is what the steel reaches.

$$f_s = f_{ye} \left[1.5 - 0.5 \left(\frac{0.12 - \varepsilon_x}{0.112} \right)^2 \right] \quad (2.1)$$

Figure 4 shows the diagrams of these three approximations for the stress-strain of reinforcing steel [24].

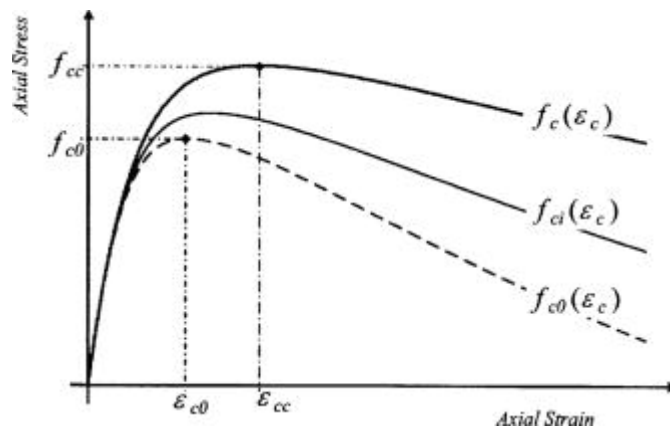


Figure 2.4. Analytical Stress–Strain Relationship for Concrete Confined by Steel Stirrups.

2.4 FIBER REINFORCED POLYMER (FRP)

Refers to a composite material composed of fiber and resin. Figure 5 is a demonstration on the structure of FRPs [22].

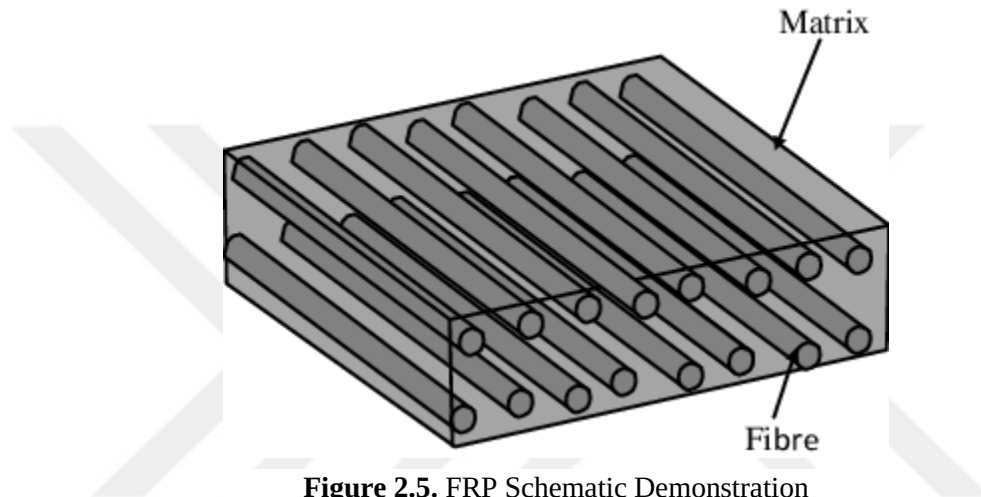


Figure 2.5. FRP Schematic Demonstration

High-strength non-metallic fibers, such as carbon, glass, and aramid fibers, encapsulated in a polymer matrix, have shown good potential for reinforcing concrete. Durable polymer fibers are available in various forms of rebars, nets, cables, ropes, tendons, sheets and different building profiles commonly known as FRP. Despite recent advances in this field, countless studies of different perspectives on its structural application have been reported in numerous articles. FRPs have been employed for structural reinforcement of structures.

The most important area in which FRP can play as a main part is in the reinforcement and improvement of existing inefficient structures, especially reinforced concrete structures that are still in use. According to its light weight, ultra-high strength and high tensile and shear strength, FRP is a suitable material for structural improvement.

In general, the performance of a composite depends on:

- a) Its ingredients
- b) Proportion of its constituent materials
- c) Carrying capacity of fiber or reinforcing fibers and how they are placed
- d) It has a constructive behavior with each other and so on.

Typically, a composite material is defined as a physical mixture on a macroscopic scale of two or more different materials that retain their physical and chemical properties and form a definite boundary with each other. In composites, there are two distinct areas which are depicted in the figure 6:

- a) Continuous phase (matrix or resin)
- b) Discontinuous phase (amplifier or fiber)

In a composite, the fibers are generally the main load-bearing members of the structure, whereas the matrix (resin) keeps them in the preferred location and arrangement and performs as a charge transfer medium between the fibers, in addition to them. Protects from environmental damage due to increased temperature or humidity.

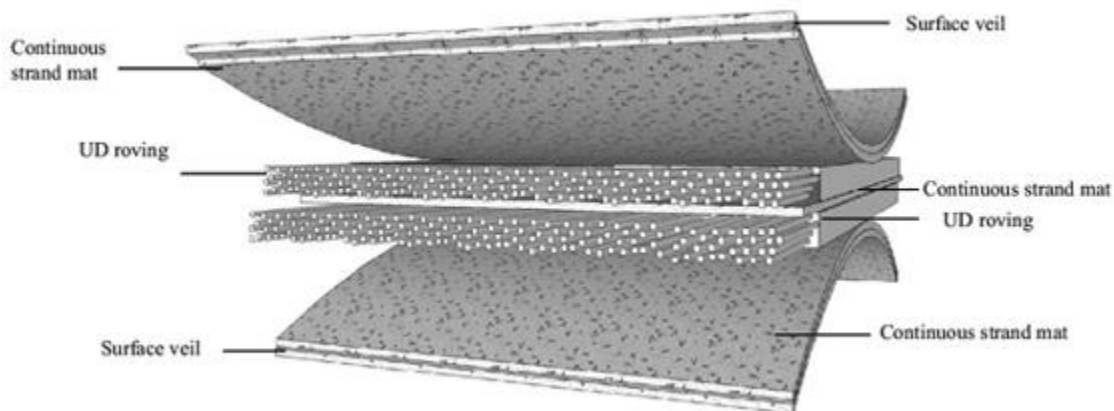


Figure 2.6. FRP Profile Schematic Representation

2.4.1 Fiber

It is made of completely elastic, brittle and very durable materials. The diameter of these fibers is between 5 and 25 microns, depending on the material. Fibers are available in a variety of sizes and materials today.

Reinforced fiber performance affected by:

- a) To position the fibers
- b) Fiber length
- c) Its shape
- d) Combining it with matrix and resin and adhesion between the two
- e) Fiber material

The name of the composite made with each of these materials begins with the first letter of the name of the fiber component. The fiber may be glass, carbon, aramid or vinyl, in which case the composite products are known as GFRP, CFRP and AFRP, respectively.

2.4.2 Matrix

The resin used as an adhesive to hold the fibers, along with its low strength, does not have a major role in the mechanical properties of the composite. In addition to holding the fibers together, the resin in the composite also acts as a factor to protect the fibers against environmental factors, as well as a stress distribution agent on the face of the composite sheet.

At a glance, the main role of the matrix (resin) is:

- a) Transfer of the cut from the reinforcing fiber to the adjacent material
- b) Protect the fiber against environmental conditions
- c) Prevent mechanical damage
- d) Control the local buckling of the fiber under pressure

2.4.3 Benefits of using FRP

FRP materials usually have a very high tensile strength, which is much greater than the tensile strength of steel materials. The high tensile strength of FRP sheets makes them very suitable for strengthening all types of structural elements, especially for concrete structures. Tensile strength of FRP sheets mainly depends on the tensile strength, volume ratio, size and cross section of the fibers used in them. The tensile strength of CFRP sheets is typically 1100 to 2200 MPa, and in some cases, even strengths above 3000 MPa have been reported. Also, the modulus of elasticity of CFRP sheets is often in the acceptable range; However, it is generally less than the modulus of elasticity of steel sheets. The modulus of elasticity of FRP sheets made of carbon, glass and aramid fibers is in the range of 100 GPa to 150, 45 GPa and 60 GPa, respectively.

The specific gravity of FRP sheets is much less than the specific gravity of steel sheets; For example, the specific gravity of CFRP sheets is between 1.5 - 1.6 g / cm³ and the specific gravity of steel is 7.9 g / cm³, which indicates that the specific gravity of CFRP sheets is about one third of the weight. Special for steel sheets. The high weight-strength ratio of CFRP sheets is one of their main advantages in their use as a concrete reinforcement.

Due to these features, the light weight of FRP makes it generally easier to move and install than steel. These features are especially vital when the installation operation is completed in restricted positions. Applying FRP sheets or sheets is like installing wallpaper. Composite fiber materials are available in many lengths, while the length of steel sheet is usually limited to 6 meters.

If the fibers and resins are properly selected and maintained, they will show very good durability [35-38]. If they are damaged at the installation site, they can be easily repaired by adding an extra layer. The use of fibrous composites does not mainly rise the weight and dimensions of the members. These different parameters in combination together ultimately increase the speed and ease of the retrofitting process. In this regard, it is assessed that about 90% of the retrofitting market in Switzerland is done using the reinforcement method with CFRP, which is due to this parameter cost reduction. In general, the benefits of the FRP system can be described as follows:

- a) High resistance to flexural and shear forces.
- b) Lightness and high resistance to weight ratio.
- c) High durability and stability.
- d) Vibration absorption capacity.
- e) Impact resistant.
- f) Moisture resistant.
- g) Transparency against UV rays.
- h) Application flexibility for surfaces in different shapes.
- i) High resistance to fatigue and periodic temperature changes.
- j) High modulus of elasticity with optimal stress distribution in the same deformation.
- k) Insulation in magnetic and electrical environments.
- l) Resistant to corrosion and chemical agents such as acids and bases.
- m) Compatibility with a variety of fire safety systems.

2.4.4 Disadvantages of FRP

The most important defect or weakness of external reinforcement of structures by FRPs is fire, intentional or accidental damage that reinforcement must be protected against these damages. One of the significant disadvantages is the use of FRP to withstand the expense of its materials. Nonetheless, evaluations should be based on the full reinforcement process, which in particular cases costs less than steel sheets. Finally, the main problem is the lack of acceptable standards and regulations.

2.4.5 Basalt fiber-reinforced polymer (BFRP)

Basalt fiber-reinforced polymers (BFRPs) are one of the most usable and applicable FRPs which can be used in different purposes [39-42]. Also, other interesting properties of these types of the FRPs are high strength and durability of the BFRPs [43-45]. Recently, the applications and study on the mechanical and structural behavior of the beams reinforced with BFRP also have been increased, significantly [44, 46, 47]. Ouyang et al. [48] have studied the effect of adding different number of BFRP layers to the RC beam on the tension side of the concrete to examine the effect of BFRP reinforcement on the flexural behavior of RC beams. They observed that the plastic hinge was occurred in the hogging region and later in the sagging region. But they found that BFRP layers can meaningfully improve the bending strength of the beam. Furthermore, many investigations have been performed to examine the influence of the BFRP layers in different size and shape on the flexural behavior of the beams [49-52].

2.5 DEEP REINFORCED CONCRETE BEAMS

Concrete deep beams have many beneficial applications, especially in tall buildings, foundations and offshore structures. According to ACI318-02 [34], a deep beam refers to a member that is loaded in one side and placed on the support in the opposite side, so that the compression elements in the member between the loads and the support can be Considered. In addition, the arrow has one of the following conditions:

- A) The free openings of the beam (l_n) are less than or equal to four times the total depth of the beam (h):

$$l_n \leq 4h \quad (2.2)$$

- B) On the beam, concentrated loads in the range of twice the depth of the beam should be applied from the support.

It should be noted that the definition of ACI318-02 of deep beam is different from previous versions of the regulations. In previous versions of the regulations, instead of satisfying one of the conditions 1 or 2, the condition of the ratio of the opening to a height less than or equal to 5 was stated [34].

2.5.1 Deep reinforced concrete beam with opening

Often the attendance of openings in deep reinforced concrete beams is inevitable due to architectural needs or the passage of utility pipes, etc.

Openings often prevent the transfer of load by the concrete compression component and greatly reduce the strength and efficiency of deep beams. Due to the high stress concentration, many cracks are created at the top and bottom of the openings. These cracks, due to high transverse strains, will reduce the effective strength of concrete. This causes them to be repaired with existing reinforcement methods to compensate for the decrease in strength and to prevent cracks and damage in the deep beam of reinforced concrete. Therefore, one of the methods that is usually recommended in this regard is the use of FRP reinforcement method, which has recently received much attention in the field of retrofitting [53].

2.5.2 Reinforcement of deep beam of reinforced concrete with opening

With the reduction of resistance and the occurrence of cracks and damage in the deep beam of reinforced concrete, due to the existence of openings, it is very essential to use a convenient method to repair and strengthen the deep beam of reinforced concrete with opening. In the meantime, using the method that has the best performance in cases such as increasing the flexural and shear capacity of deep reinforced concrete beams with opening, cost-effectiveness, execution speed, durability, and other effective parameters, among other methods of reinforcement are very It is important.

For improving and strengthening deep reinforced concrete beams with opening, FRP sheets due to high strength, good flexibility in different operating conditions and without causing much

physical change in the shape and dimensions of the member, a very suitable option for use in repairing and strengthening concrete beams. Armed with an opening.

In deep reinforced concrete beams with opening, the connection of FRP sheet to the tensile zone of concrete so that the direction of its fibers is in the longitudinal direction of a flexural member, increases the flexural strength of the member.

The employment of FRP sheets as external stirrups is to increase the shear strength of reinforced concrete sections. In this method, FRP plates are glued to the sides of the beam so that the direction of the fibers is perpendicular to the longitudinal axis of the beam or inclined. To have a U-shaped outer stirrup, FRP sheets are installed continuously on both sides and under the beam, which also improves the inhibitory flexural reinforcement of FRP. For greater shear reinforcements efficiency, it is obligatory to provide end restraint. For example, in cases where the restraint length is limited, the shape of the end restraint is provided by installing supplementary longitudinal strips to the end of the U-legs. In order to circumvent rupture of FRP stirrups according to stress concentration in the cross-section corners of the beam, these corners should be rounded to a radius of at least 35 mm.

3. METHODS AND SIMULATION

In the current work, the flexural behavior of Reinforced concrete beams is investigated using four-point flexural test to observe the effect of FRP laminates as a strengthening additive on Reinforced Concrete (RC) deep beams. Additionally, two different web openings with the circular shape and square shape were used for different cases to check the effect of web opening and the shape of them on the flexural strength of the RC deep beams.

An important material property, flexural strength, which also is well-known as the rupture modulus, or transverse strength of rupture or strength of bend, can be also described as the maximum stress which is applied in a material before it yields. There are different types of experiment to measure the flexural strength and recognize the flexural behavior of a metal, plastic, or composite. Three point bending and four-point bending tests are two most common used experiment to measure the flexural behavior of the materials. The schematic of four-point bending test is illustrated in Figure 3.1. From this schematic it can be understood that during the loading on the beam the upper half of the materials will be under a compression stress and the bottom half of that is under a tension stress. These two different mechanisms of loading are applied on the beam during the bending test to find out the flexural strength of the beam. Generally, the maximum at the center of the beam on the concave side of the bend the compressive stress is the maximum range of the hole system. On the other hand, the tensile stress at the center of convex side of the beam is the maximum value. The aforementioned outer and inner points are stated as the 'extreme fibers'. Commonly beams fabricated by different materials fail from the side where it is under the tensile stress prior to failing under the compressive stress, therefore the max. tensile stress which was suffered prior to failure of the beam is the flexural strength of that.

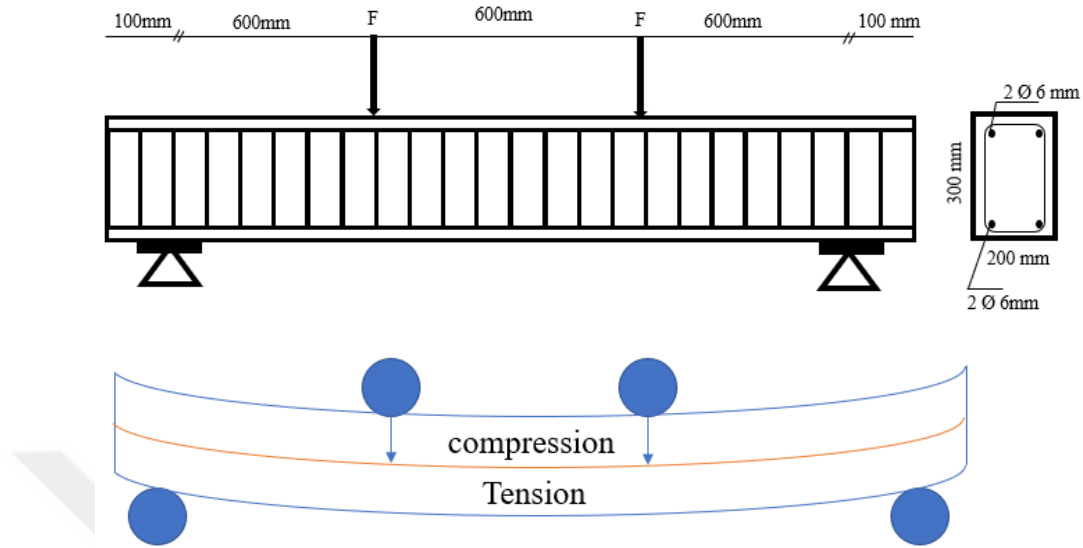


Figure 3.1: Schematic of System Design and Four-Point Flexural Test.

In order to simulate the four-point bending in ABAQUS, different steps have been done. In this section the different steps of the modeling and simulation of the RC beams and web openings as well as FRP laminates are listed and explained briefly.

3.1 PART MODULE

As shown in Fig. 3.1, the first section of modelling in ABAQUS software is part module. In the current thesis, parts such as BFRP layer, bars, beam, stirrups, bottom rigid bodies and top rigid bodies were designed and modeled in the part section of ABAQUS. The dimensions of the concrete beam were 200mm, 300mm, and 2000mm for width, height, and length, respectively.

4 steel bars and 18 stirrups were utilized to reinforce the concrete throughout the beams. Also, in order to support the beam from both sides rigid bodies were used as well as tow rigid bodies at the top of the beam to make the displacement and load on the beam during the four point bending test.

For the beam firstly the cross-section of the beam was designed then it extruded to the length of 2000mm. Furthermore, BFRP layer were designed as a U shape to wrap the beam from the

bottom and both sides of the beam. The length of the beam was 1800mm to wrap the beam between two supports at the bottom of the beam. The design of the BFRP is demonstrated in Fig. 3.3.

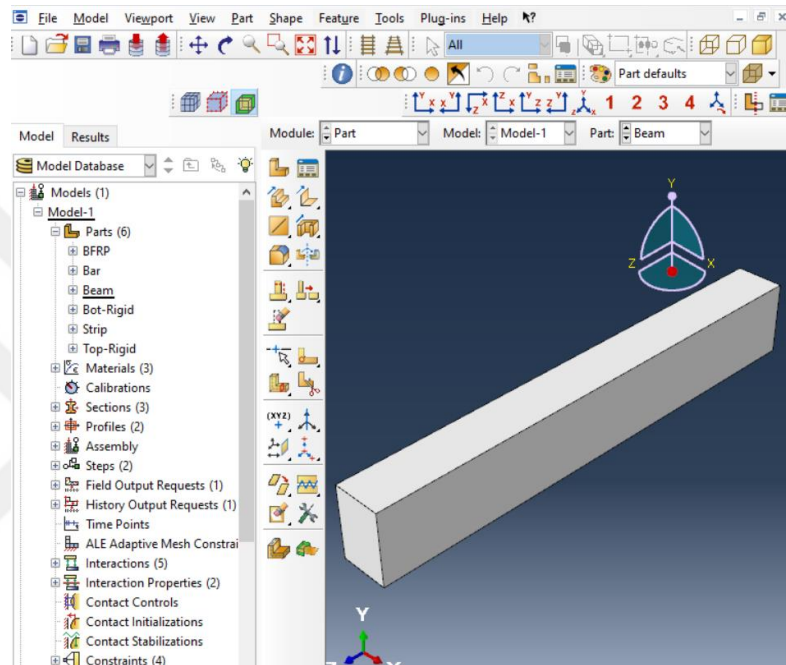


Figure 3.2. Part module environment and created parts.

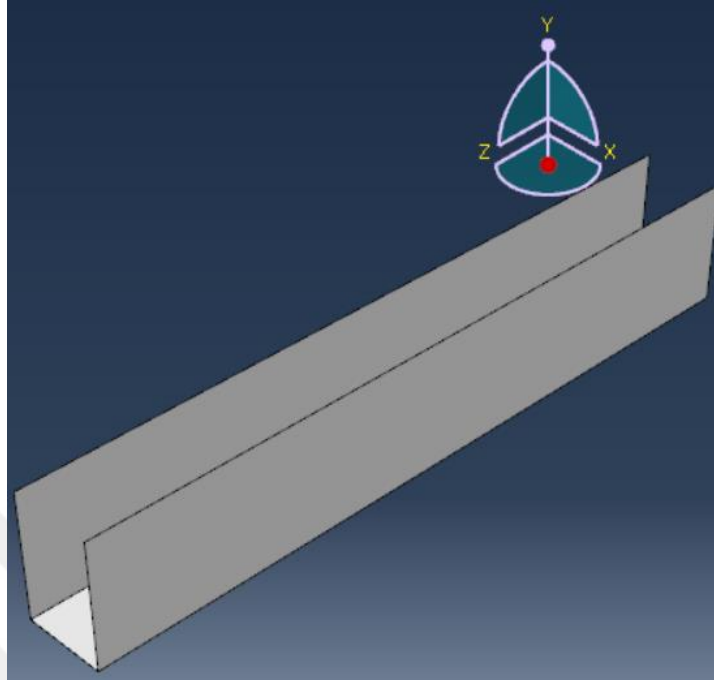


Figure 3.3. BFRP model created in part module of the ABAQUS.

3.2 PROPERTY MODULE

In this module, all the properties of the materials used in the simulation, were added. As shown in Fig. 3.4, the materials used in the current study was BFRP, concrete, and steel, therefore all the mechanical properties of these materials were defined to analyze the flexural behavior of the elements during the simulation.

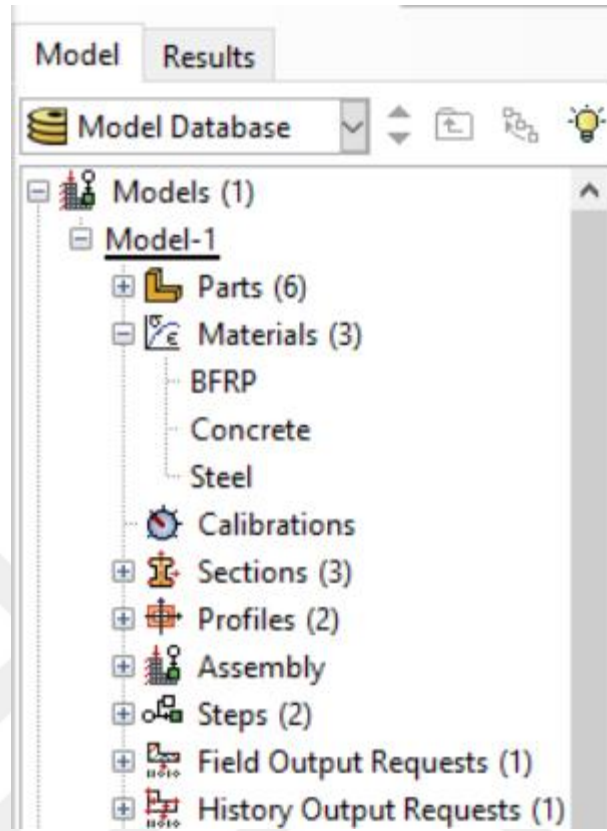


Figure 3.4. Property module of ABAQUS.

To do this, the mechanical behavior of BFRP, such as Hashin damage, density and elastic properties were defined to the software (see Fig. 3.5). Also, for elastic properties of BFRP, the lamina type was considered with specific modulus taken from the literature shown in Fig. 3.6

✚ Edit Material ✕

Name: BFRP

Description:

Material Behaviors

- Hashin Damage
- Density
- Elastic

General Mechanical Thermal Electrical/Magnetic Other

Hashin Damage

Alpha:

☐ Use temperature-dependent data

Number of field variables:

Data

	ongitudinal Tensil	ongitudinal Compres	Transverse Tensil	Transverse Compres	ongitudinal Streng
	Strength	Strength	Strength	Strength	Strength
1	580000000	280000000	100000000	150000000	100000

Figure 3.5. Material properties of BFRP.

Density

Elastic

General Mechanical Thermal Electrical/Magnetic Other

Elastic

Type:

☐ Use temperature-dependent data

Number of field variables:

Moduli time scale (for viscoelasticity):

☐ No compression

☐ No tension

Data

	E1	E2	Nu12	G12	G13
1	16000000000	2800000000	0.25	2800000000	2800000

Figure 3.6. Elastic mechanical behavior of BFRP.

3.3 ASSEMBLY MODULE

In this module, all the parts were assembled as shown in Fig. 3.7 and Fig. 3.8.

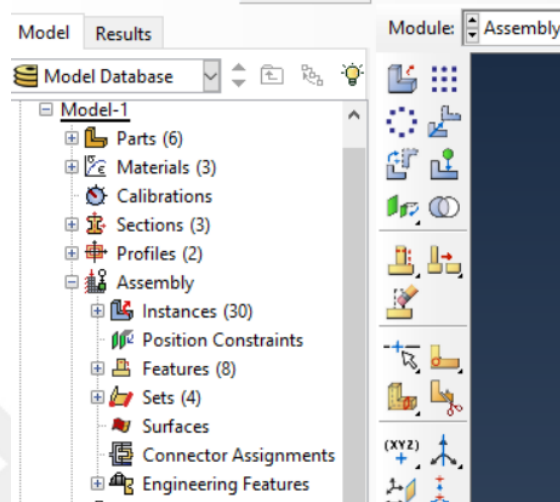


Figure 3.7. Assembly module of ABAQUS.

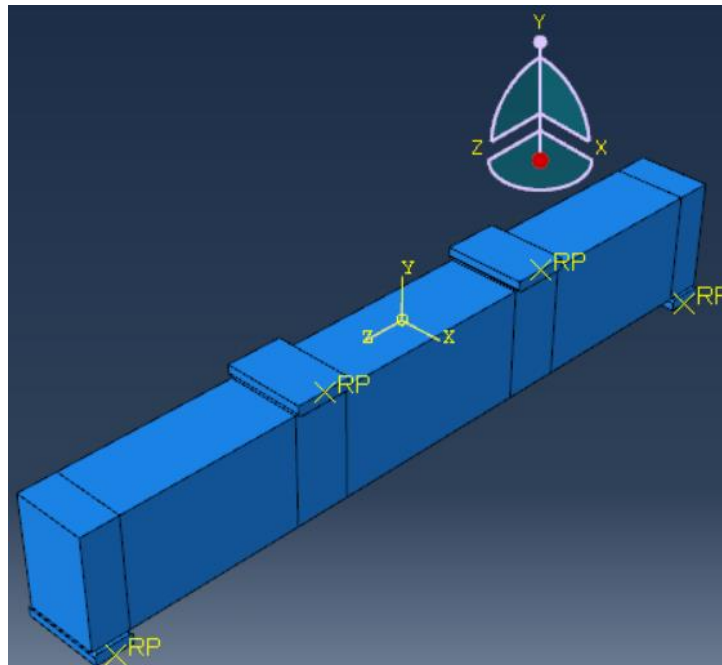


Figure 3.8. Assembly of the four point bending test simulated in ABAQUS.

Furthermore, Fig. 3.9 demonstrates the embedded region contains 4 bars and the stirrups inside of the concrete beam.

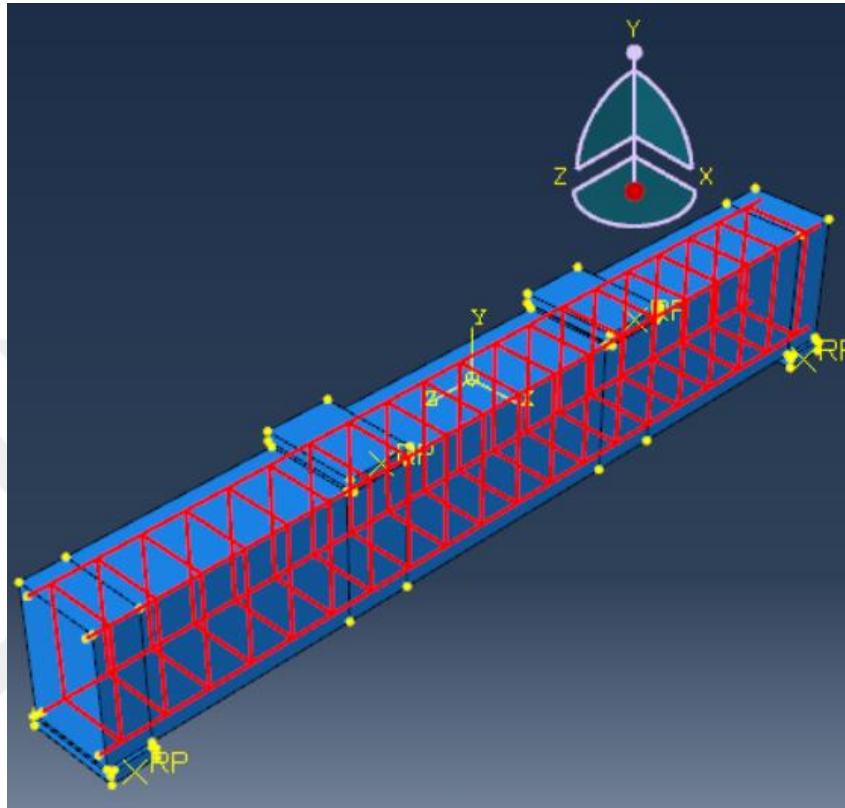


Figure 3.9. Embedded region inside the concrete beam.

3.4 STEP AND INTERACTION MODULES

In the step and interaction modules, the boundary conditions and contacts between the different surfaces and parts have been defined. Also, the types of the contacts and constraints between the supports and beam, loading rigid bodies and beam, as well as beam and BFRP were defined. The different section of these modules is demonstrated in Fig. 3.10.

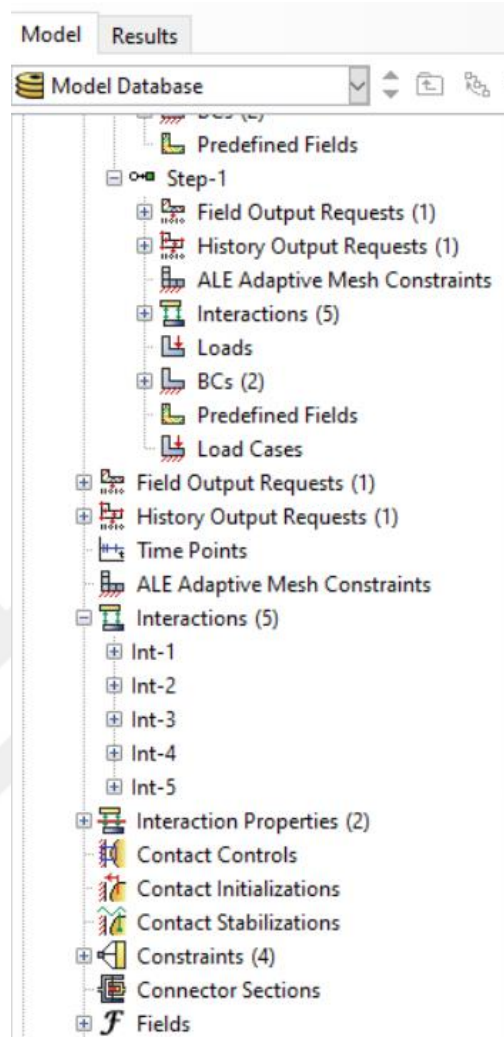


Figure 3.10. The step and interaction parts of ABAQUS.

3.5 LOAD MODULE

In this module the supports at both sides of the beam is defined and the load were applied using two rigid bodies at the top of the beam as demonstrated in Fig. 3.11. The encastre boundary condition was defined for the supports.

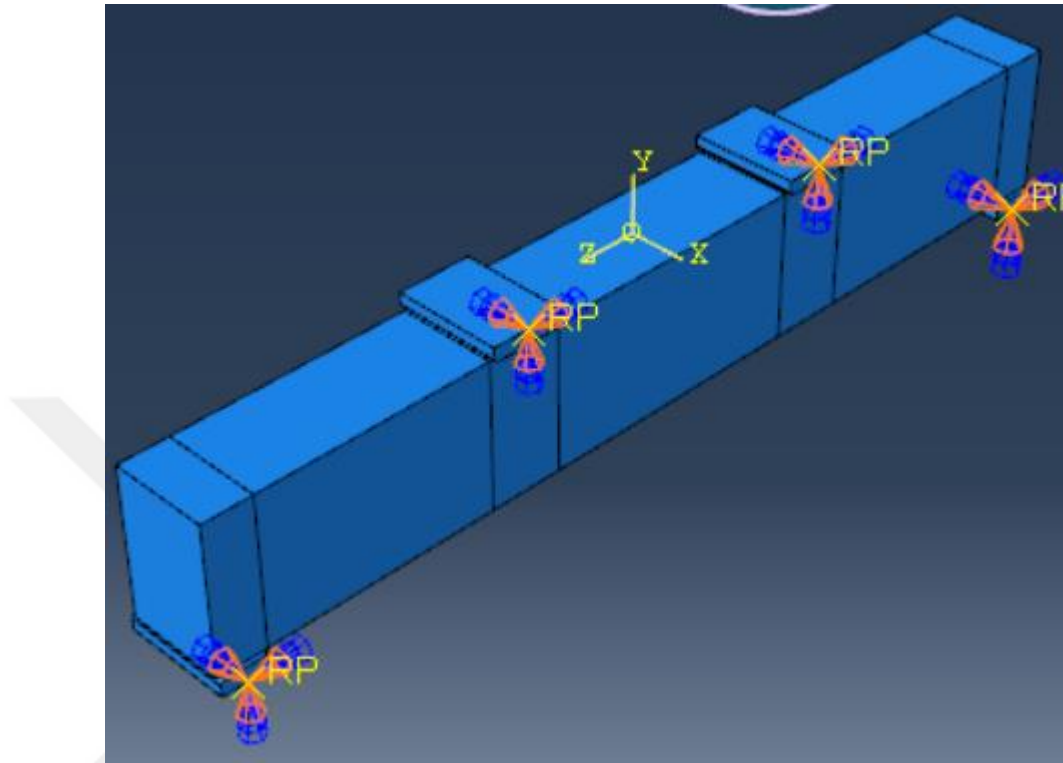


Figure 3.11. The location of the loadings and supports on the beam.

3.6 MESH MODULE

Mesh module is one of the most important part of the simulation which can effectively influence the results of the simulation. With decreasing the size of the mesh the results of the simulation may be more reliable and with better alignment with the experimental results, however, decreasing the size of the mesh and subsequently increasing the number of the nodes and elements significantly increase the time of the simulation. In the current study, the approximate global size was chosen as 0.04 with a maximum deviation factor of 0.1 to optimize the time of the simulation as much as possible. Figure 3.12 and Fig. 3.13 illustrate the meshed beam and BFRP layer, respectively.

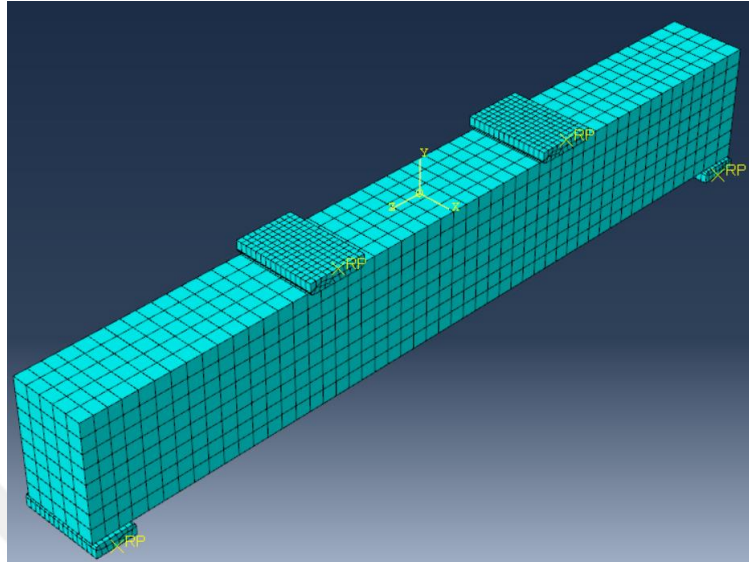


Figure 3.12. Mesh of the beam and setup.

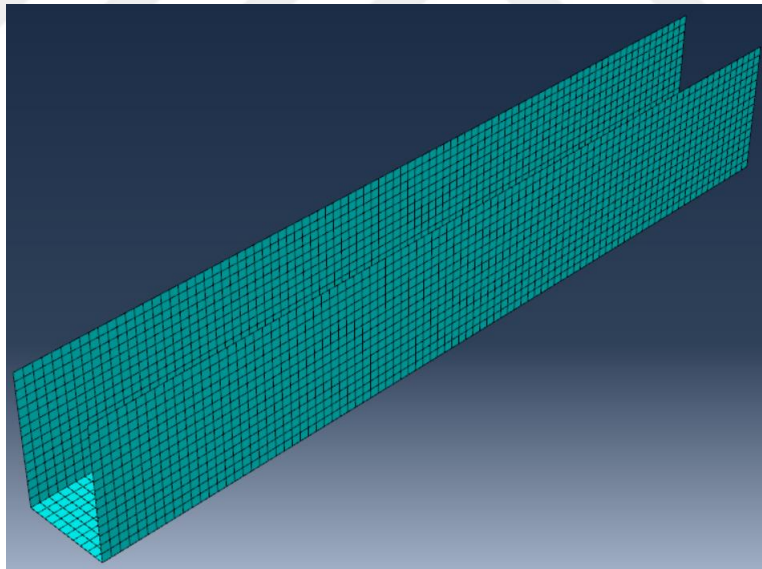


Figure 3.13. Meshed BFRP.

4. RESULTS AND DISCUSSION

The main purpose of this paper is to recommend a model to simulate four-point bending test of the beams with and without web openings and BFRP layer by explicit solver of ABAQUS. To analyze the tensile and flexural behavior conditions, the ABAQUS/Explicit is utilized. Table 4.1 describes the properties of the material used for failure modeling [54]. Also, compressive stress vs strain curve and tensile behavior of the concrete used in the current simulation are demonstrated in Fig. 4.1 and Fig. 4.2, respectively.

Table 4.1. Properties of the material used for failure modeling [54].

Elastic (GPa)	E_{11} 16 (Bending), 25 (Tensile)	E_{22} 2.8	ν_{12} 0.25	G_{12} 2.8	G_{13} 2.8	G_{23} 2.65
Damage initiation (MPa)	X-T 580	X-C 280	Y-T 100	X-C 150	S-L 100	S-T 100

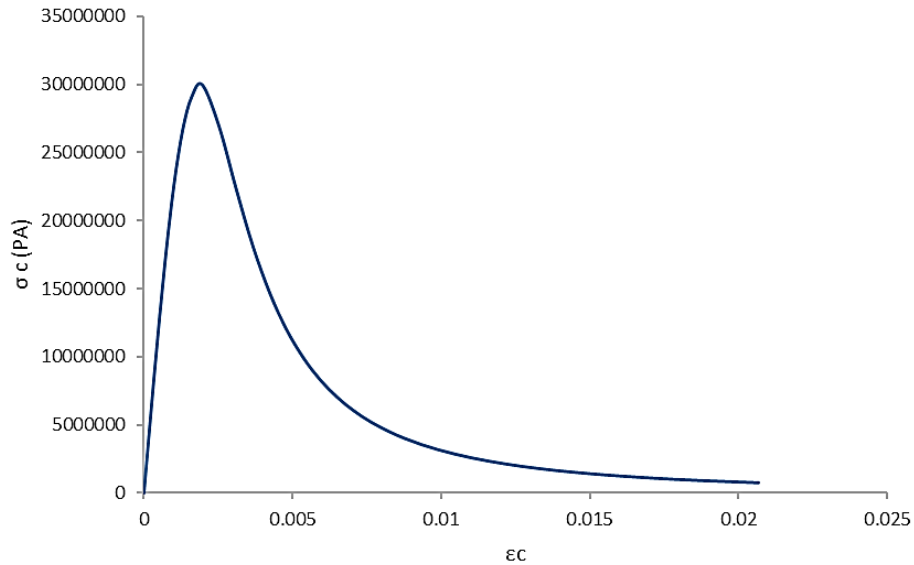


Figure 4.1: Compressive Behavior of Concrete Employed In This Simulation.

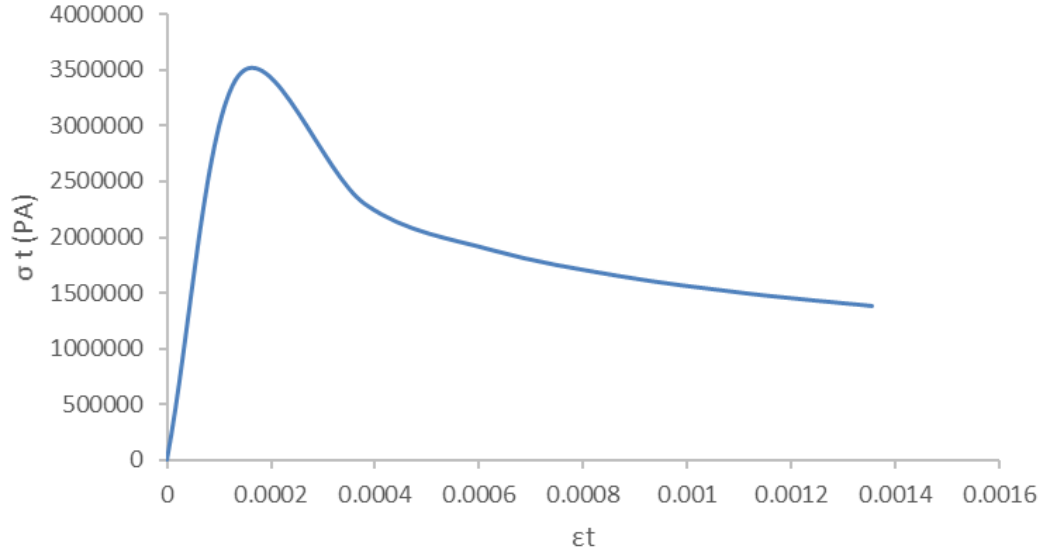


Figure 4.2. Tensile behavior of concrete used in this simulation.

In order to prevent the repetition of the definitions for the different cases of the beam, Table 4.2 was prepared with the name of the conditions and their abbreviations.

Table 4.2. The name and related abbreviation of the models.

N	Model Name	Abbreviation
1	Reinforced Concrete Beam	RCBeam
2	Reinforced Concrete Beam with circular web opening	RCBeam-C
3	Reinforced Concrete Beam with rectangular web opening	RCBeam-R
4	Reinforced Concrete Beam with Wrapped BFRP	RCB-BFRP-Wrapped
5	Reinforced Concrete Beam with circular web opening wrapped by BFRP	RCB-C-BFRP-Wrapped
6	Reinforced Concrete Beam with rectangular web opening wrapped by BFRP	RCB-R-BFRP-Wrapped

4.1 REINFORCED CONCRETE BEAM WITHOUT WEB OPENING

The RC beams with and without BFRP were tested using four point bending method. The outcomes of the simulation after applying a displacement control test can be seen in Fig. 4.3 and Fig. 4.4 for RCBeam and RCBeam-BFRP-Wrapped, respectively.

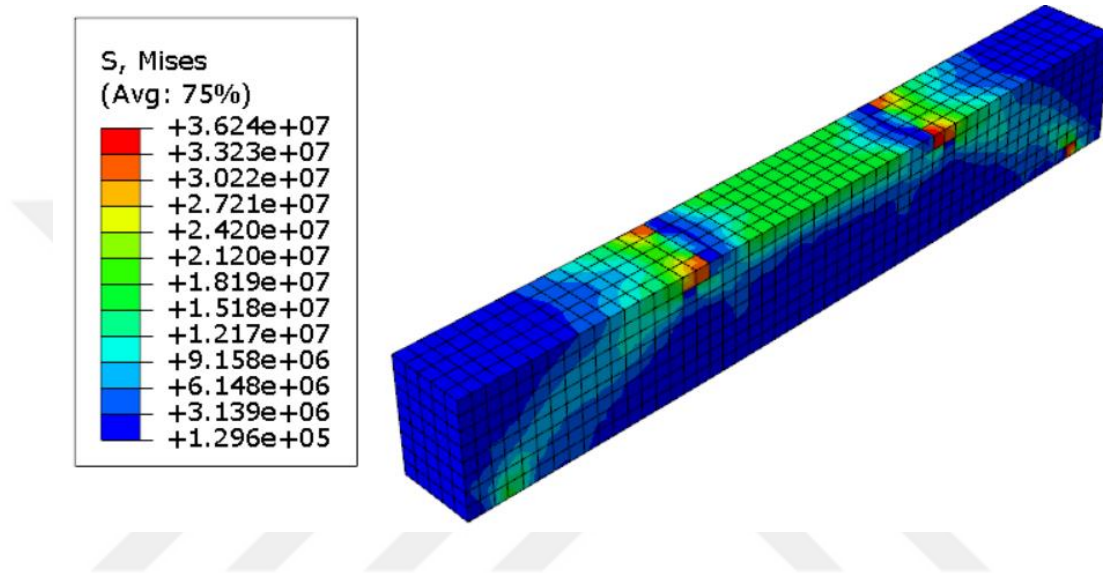


Figure 4.3. Stress distribution on the RCBeam.

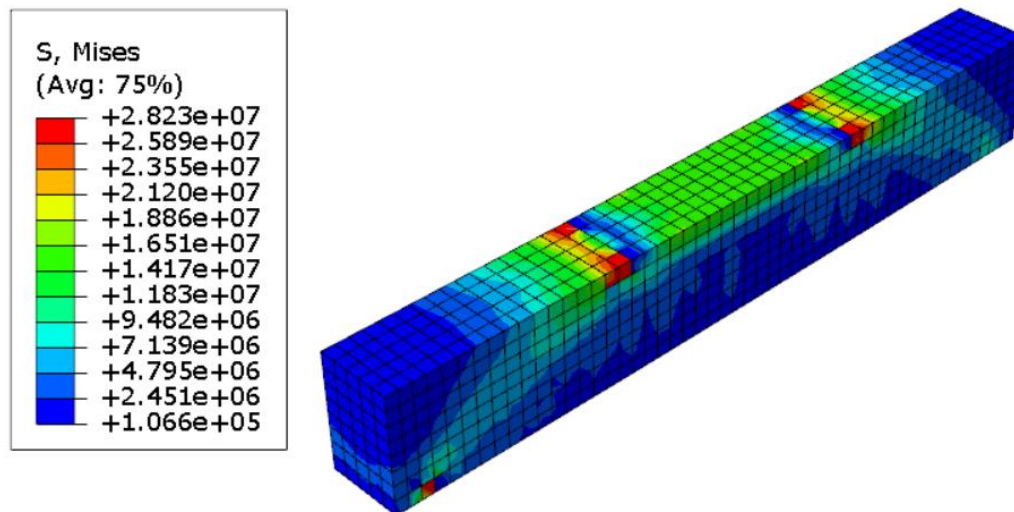


Figure 4.4. Stress distribution on the RCBeam-BFRP-Wrapped.

With comparing the results of Von Mises stress of both RCBeam and RCBeam-BFRP-Wrapped conditions, it can be clearly seen that the BFRP has decreased the stress on the beam after applying the same displacement (see Fig. 4.3 and Fig. 4.4). Also, it can be observed that the stress level at supports and the applied zones are maximum.

The result of the displacement magnitude is shown in Fig. 4.5 in which the maximum Strain was in between two loading part at the center of the beams. And the least amount at the corneres on the supports.

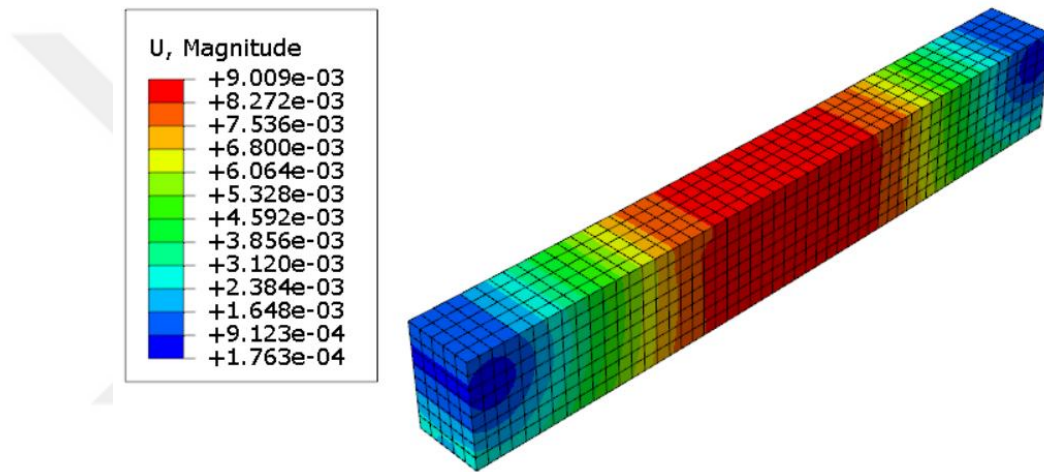


Figure 4.5. Strain magnitude on the beam after loading.

Furthermore, the supporting function of BFRP-Wrapped layer can be observed using the stress distribution of this layer individually in Fig. 4.6 and Fig. 4.7. These figures demonstrate that during the loading 176.8 MPa is carried out by the BFRP part and the stress concentrations was on the loading zones and also the bottom parts which were in contact with the bottom of the beam from the exact cross-section in which loads have been applied. This can be obviously observed from the bottom view illustrated in Fig. 4.7.

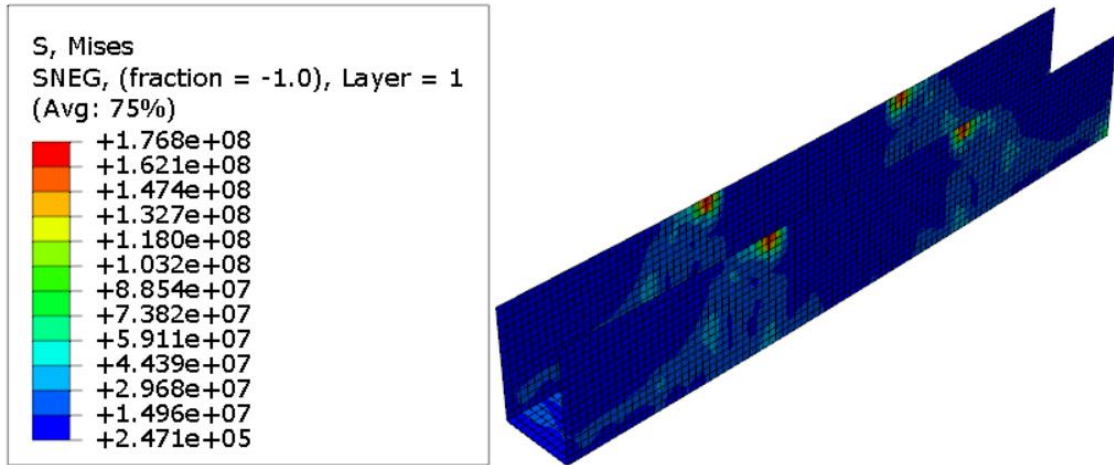


Figure 4.6. Stress distribution on the BFRP-Wrapped individually.

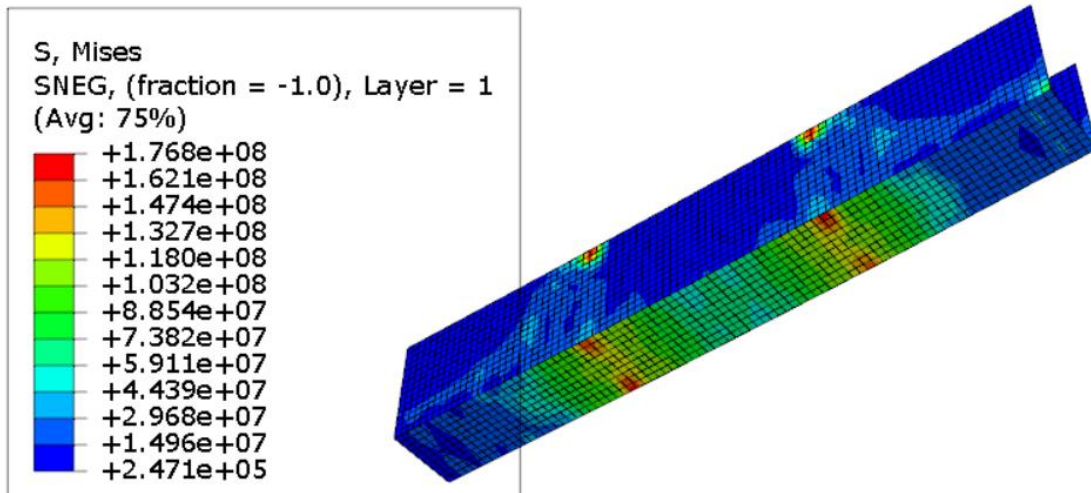


Figure 4.7. Stress distribution on the BFRP-Wrapped individually from the bottom view.

Also, the stress distribution on the embedded steel set can be seen in the Fig. 4.8. It can be observed that in some sections steel part was also yielded due to the high amount of deflection administrated on the beam and increasing the amount of deflection passed steel parts to the plastic region.

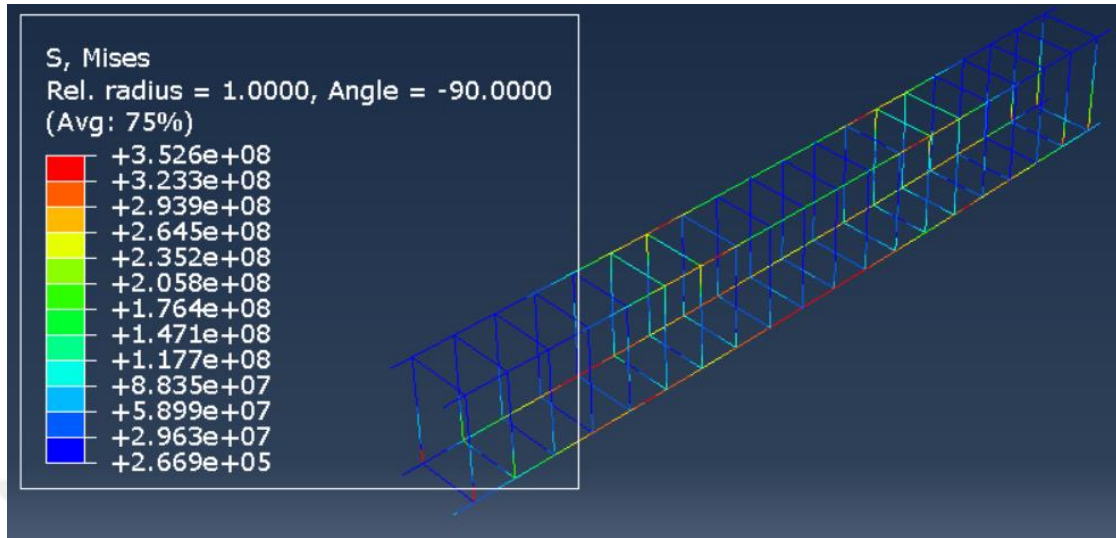


Figure 4.8. Stress distribution on the bars and stirrups of the embedded region inside of the beam.

In Fig. 4.9 and Fig. 4.10, the effect of BFRP layer of the yielding initiation and propagation also can be observed. Considering the Fig. 4.9, it can be easily observed that the region around the bottom supports and also top rigid bodies which loads have been applied from those regions are the starting points of the failure. However, the bottom central region of the beam is also a critical region that cracks may start from this part according to the low tensile strength of the concrete. But with the addition of the BFRP wrapped layer in Fig. 4.10, it can be seen that the yielding nodes are notably decrease at the same level of deformation which is related to the supporting function of the BFRP layer on the crack initiation and propagation of the beam.

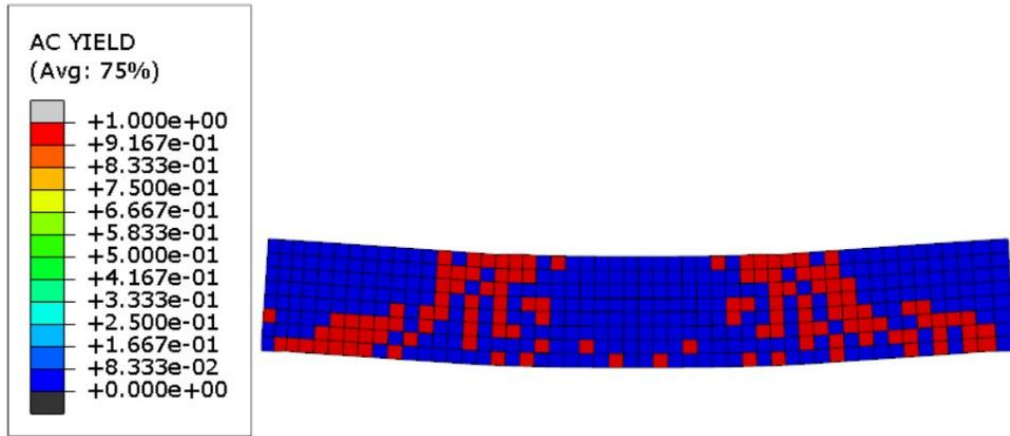


Figure 4.9. Yielding criteria of the RC beam under the flexural bending without BFRP

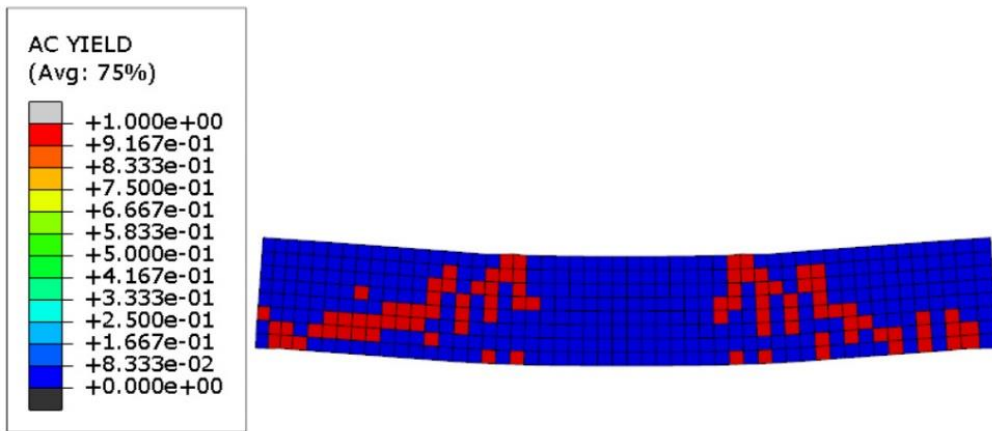


Figure 4.10. Yielding criteria of the RC beam with wrapped BFRP layer under the flexural bending.

4.2 REINFORCED CONCRETE BEAM WITH CIRCULAR WEB OPENING

The RC beams with circular opening with a diameter of 18mm at the center of the beams with and without wrapped BFRP were tested with four point bending system. The outcomes of the simulation after applying a displacement control test can be seen in Fig. 4.11 and Fig. 4.12 for RCBeam-C and RCBeam-C-BFRP-Wrapped, respectively.

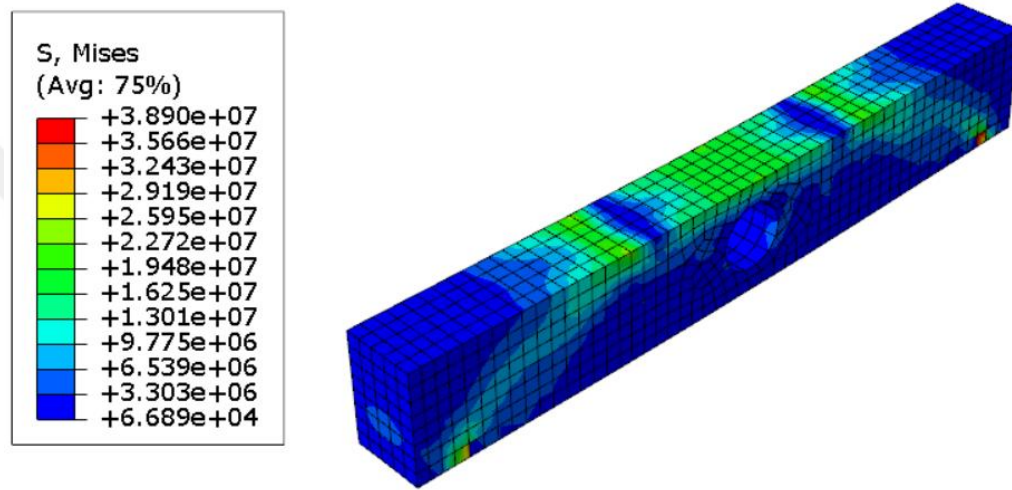


Figure 4.11. Stress distribution on the RCBeam-C.

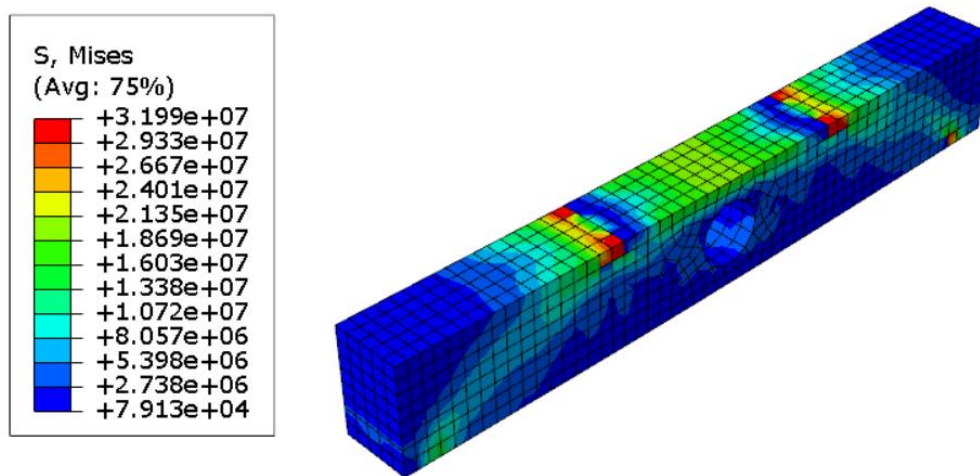


Figure 4.12. Stress distribution on the RCBeam-C-BFRP-Wrapped.

With comparing the results of Von Mises stress of both RCBeam-C and RCBeam-C-BFRP-Wrapped cases, it can be observed that the BFRP has decreased the stress on the beam after applying the displacement (see Fig. 4.11 and Fig. 4.12). Moreover, it can be understood that the stress level at supports, and the applied zones are still maximum. However, the result of the displacement magnitude is shown in Fig. 4.13 in which the maximum displacement was in between two loading part at the center of the beams and the lowest at the sides of the supports.

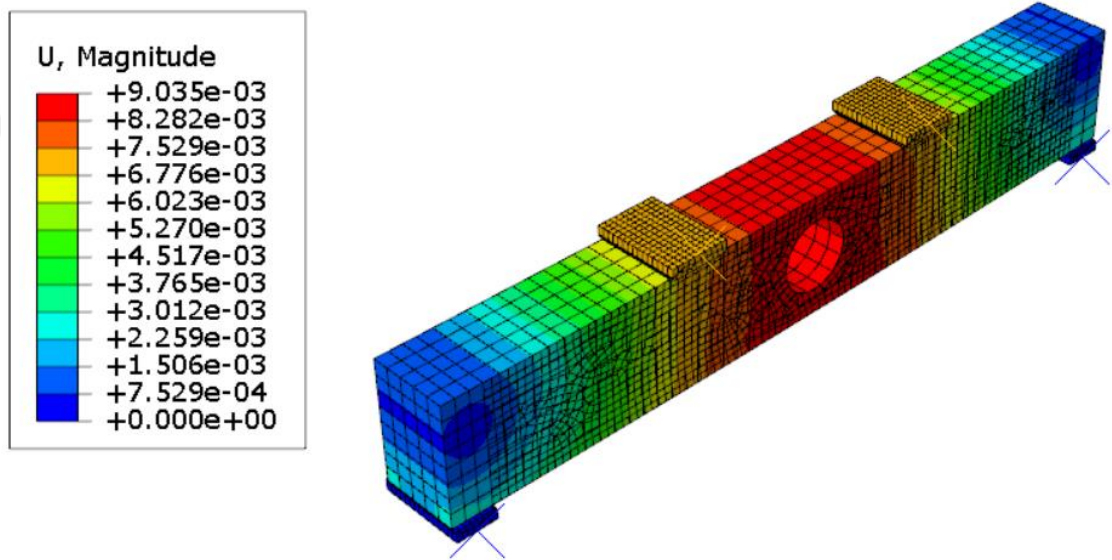


Figure 4.13. Strain magnitude on the system after loading.

Furthermore, the supporting function of BFRP-Wrapped layer can be observed using the stress distribution of this layer individually in Fig. 4.14 and Fig. 4.15. These figures demonstrates that during the loading 183.9 MPa is carried out by the BFRP part and the stress concentrations was on the loading zones for the top part of the BFRP. Furthermore, Fig. 4.15 depict that the stress concentration of the BFRP at the bottom was transformed to the center of the layer due to the circular web opening at the center of the beam and BFRP layer. Also, this web opening has increased the level of the stress on the BFRP slightly in comparison with the beam without web opening.

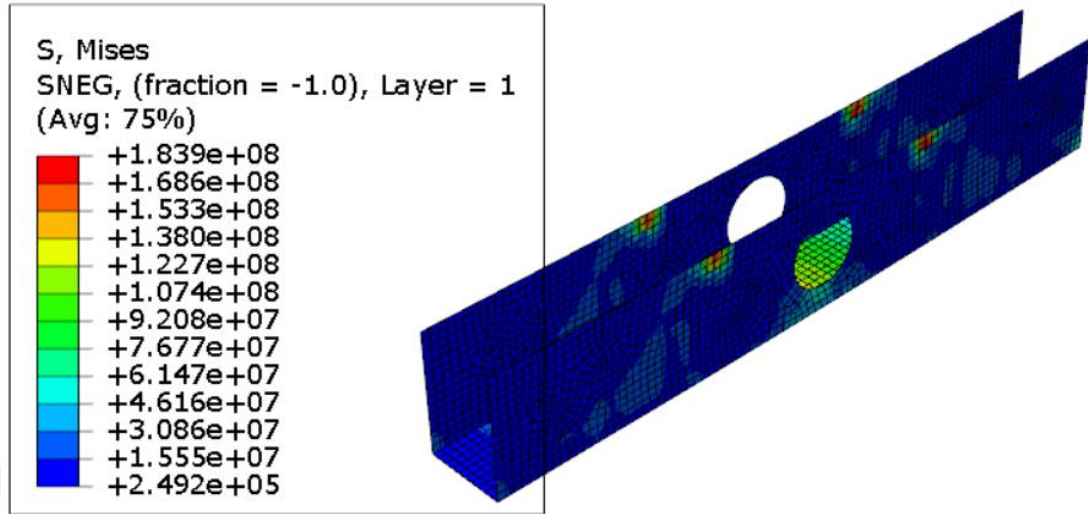


Figure 4.14. Stress distribution on the BFRP-Wrapped with circular web opening individually.

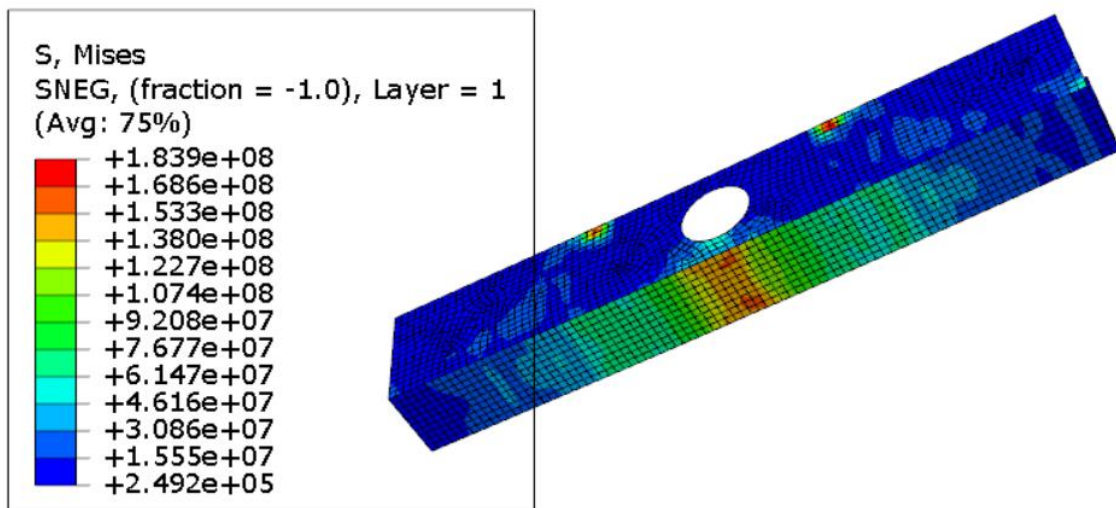


Figure 4.15. Stress distribution on the BFRP-Wrapped with circular web opening individually from the bottom view.

In Fig. 4.16 and Fig. 4.17, the influence of BFRP wrapped layer of the yielding initiation and propagation also can be observed. Considering the Fig. 4.9, it can be easily observed that the region around the bottom supports and also top rigid bodies which loads have been applied from those regions are the starting points of the failure. However, the bottom central region of the beam is also a critical region that cracks may start from this part according to the low tensile strength of the concrete. But with the addition of the BFRP wrapped layer in Fig. 4.17, it can be

seen that the yielding nodes are notably decrease at the same level of deformation which is related to the supporting function of the BFRP layer on the crack initiation and propagation of the beam.

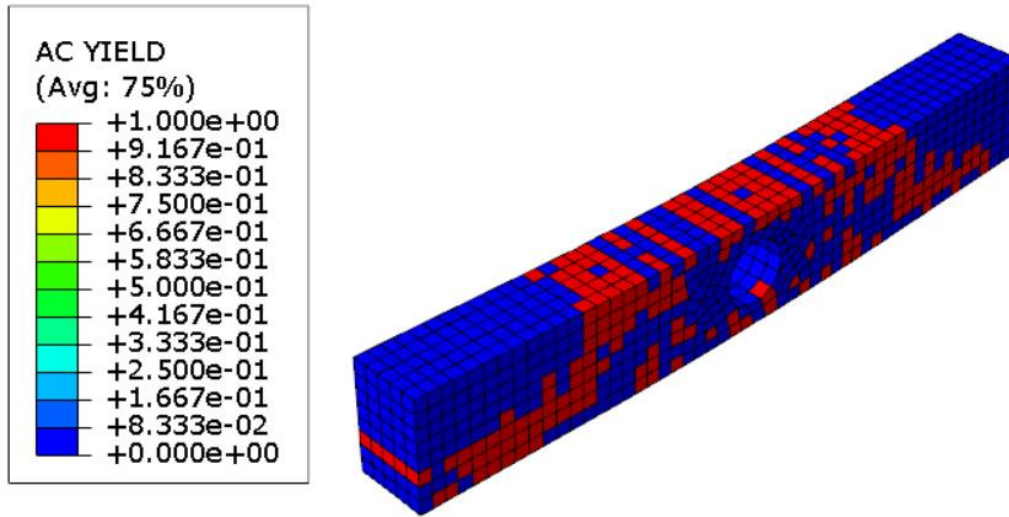


Figure 4.16. Yielding criteria of the RCBeam-C under the flexural bending without BFRP

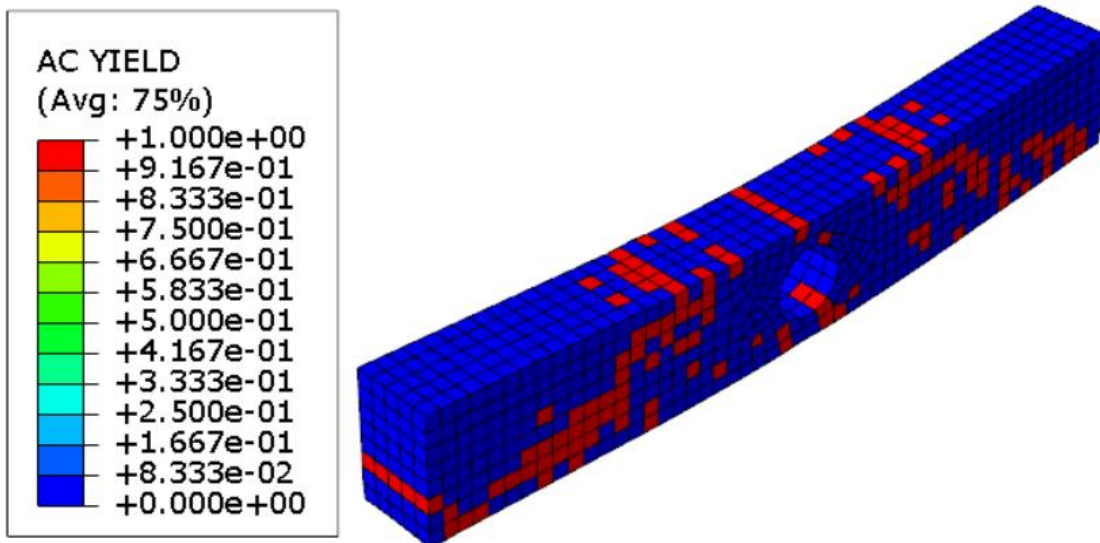


Figure 4.17. Yielding criteria of the RCBeam-C-BFRP-Wrapped layer under the flexural bending.

4.3 REINFORCED CONCRETE BEAM WITH RECTANGULAR WEB OPENING

The RC beams with a rectangular web opening at the center of the beam with the side dimensions of 18 mm with and without BFRP were tested using four point bending method. The Strain applied on the beams was shown in Fig. 4.18.

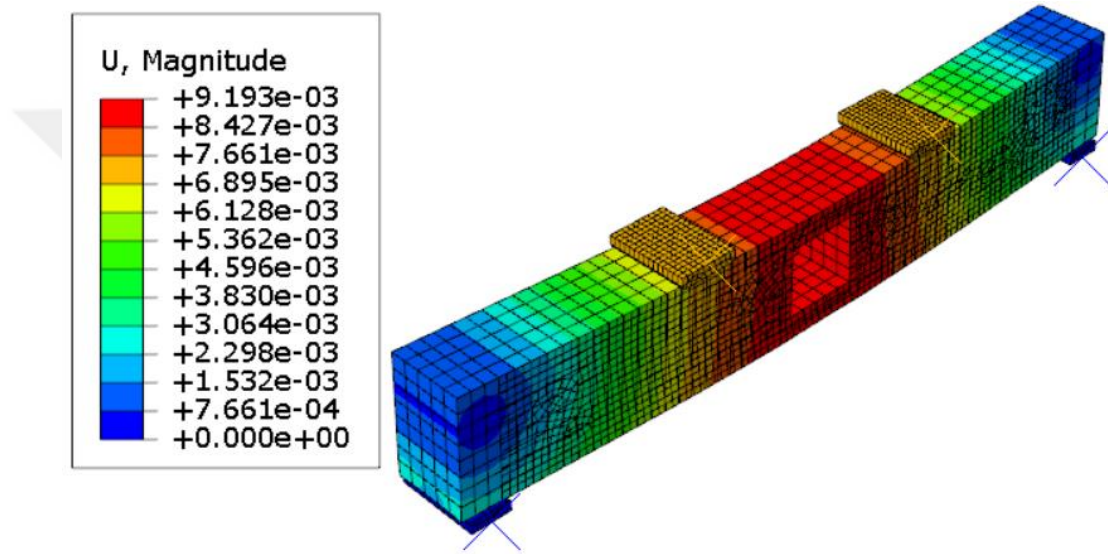


Figure 4.18. Strain magnitude on the beam after loading.

Also, after applying the load on the beams with and without BFRP layers it was observed that similar to the other cases the maximum Von Mises stress level of the BFRP wrapped beam was lower than that of without BFRP with rectangular web opening. Fig. 4.19 shows that the corresponding stress on the RCBeam-R-BFRP-Wrapped was 37.19 MPa. Also according to the outcomes of the simulation for the beam with rectangular web opening and without BFRP layer, the stress value for that case was 44.21 MPa which was the highest according to the stress concentration on the edge of the square shape web opening.

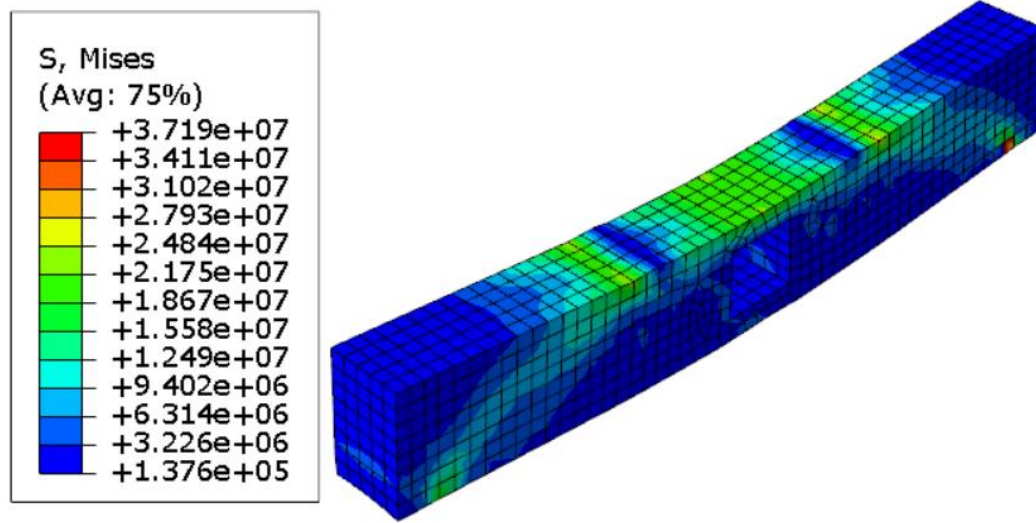


Figure 4.19. Stress distribution on the RCBeam-R-BFRP-Wrapped..

The result of the displacement magnitude is shown in Fig. 4.5 in which the maximum displacement was in between two loading part at the center of the beams. And the least amount at the corneres on the supports.

Moreover, the supporting role of BFRP-Wrapped layer with rectangular web opening can be observed using the stress distribution of this layer individually in Fig. 4.20 and Fig. 4.21. These figures demonstrates that during the loading 231.1 MPa is carried out by the BFRP layer and the stress concentrations was on the loading zones at the top of the U shape layer and also at the bottom parts it is shifted and concentrated on the center of the U shape where it had supported the center of the beam. This shift is due to the location of the rectangular web opening at the center of the beam.

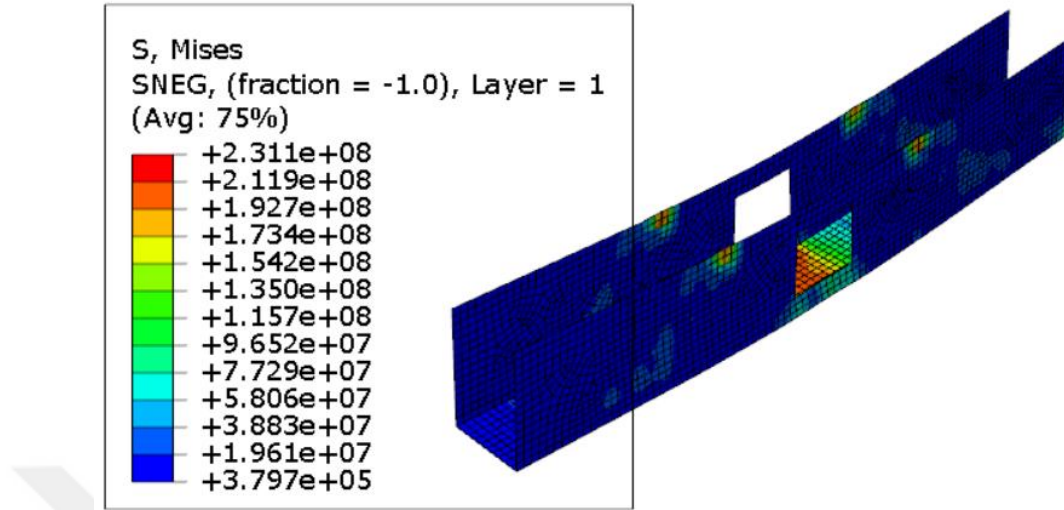


Figure 4.20. Stress distribution on the BFRP-Wrapped with rectangular web opening individually.

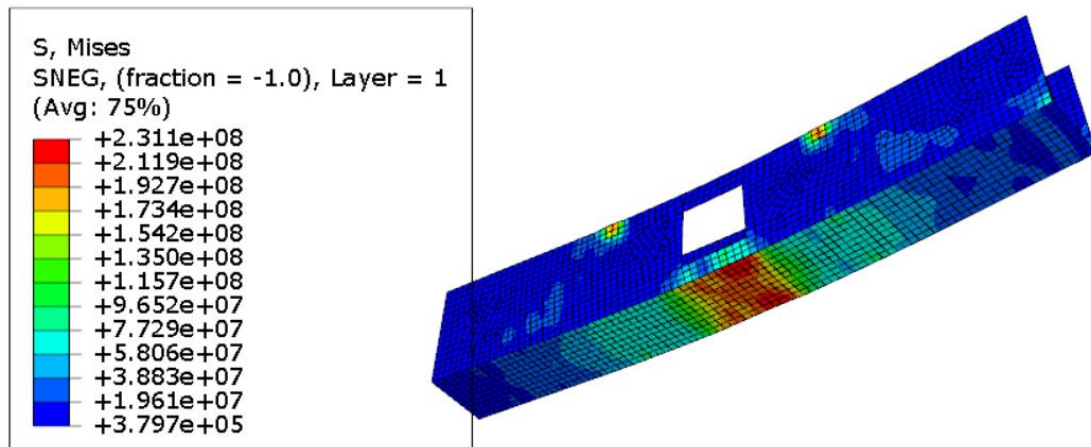


Figure 4.21. Stress distribution on the BFRP-Wrapped with rectangular web opening individually from the bottom view.

In Fig. 4.22 and Fig. 4.23, the effect of BFRP layer of the yielding criteria of the RC beams with rectangular web opening has been analyzed. Considering the Fig. 4.22, it can be noticed that the region around the bottom supports and also top rigid bodies has some concentrations of yielding elements exactly like the beam without web opening. But the edges of the rectangular web opening is also added to the critical region where the elements can start yielding. However, the

bottom central region of the beam is also a critical region that cracks may start from this part according to the low tensile strength of the concrete. On the other hand, with the BFRP wrapped layer in Fig. 4.23, it can be imagined that the yielding nodes are markedly reduce due to the supporting role of the BFRP layer on the crack initiation and propagation of the beam.

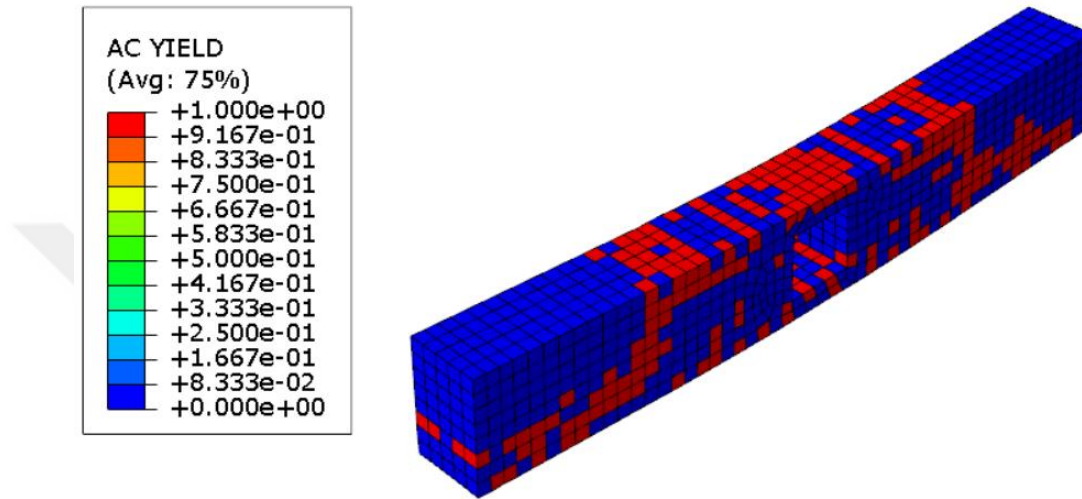


Figure 4.22. Yielding criteria of the RCBeam with rectangular web opening under the flexural bending without BFRP.

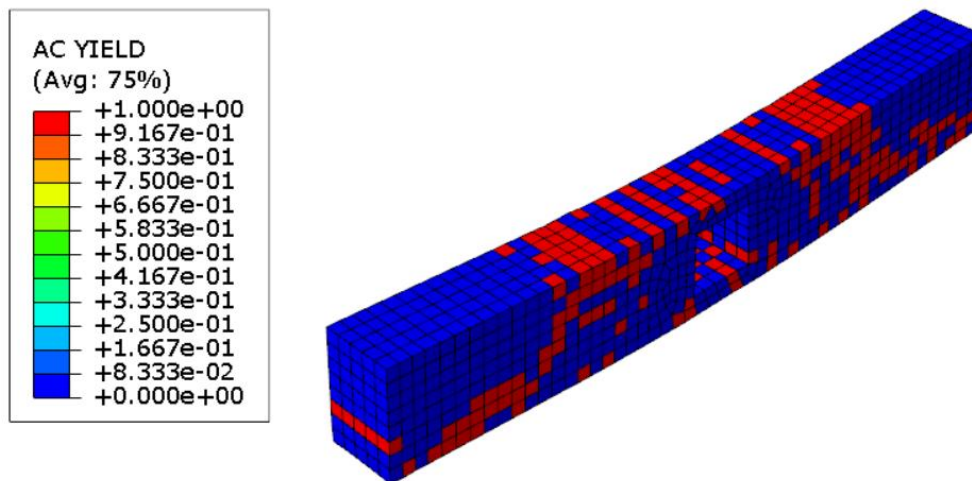


Figure 4.23. Yielding criteria of the RCBeam with rectangular web opening and with wrapped BFRP layer under the flexural bending.

beam After applying a displacement control flexural test on the beams, the results of Max. von Mises stress were recorded for all conditions and compared as shown in Table 4.2. Considering the results of the simulation, it can be understood that for both cases of RC beam with and without BFRP, with using web opening on the center of the beam, the Max. von Mises stress were enhanced noticeably. Furthermore, rectangular opening has higher stress than the circular opening. This can be related to the stress concentration on the corners of the rectangular web opening. These regions may be the high potential zones for crack initiation and propagation throughout the flexural test.

Table 4.3: The results of Max. von Mises stress for each condition with their abbreviations.

Model Name	Abbreviation	Max. Von Mises stress in Beam (MPa)
Reinforced Concrete Beam	RCBeam	36.24
Reinforced Concrete Beam with circular web opening	RCBeam-C	38.90
Reinforced Concrete Beam with rectangular web opening	RCBeam-R	44.21
Reinforced Concrete Beam with Wrapped BFRP	RCB-BFRP-Wrapped	28.27
Reinforced Concrete Beam with circular web opening wrapped by BFRP	RCB-C-BFRP-Wrapped	31.99
Reinforced Concrete Beam with rectangular web opening wrapped by BFRP	RCB-R-BFRP-Wrapped	37.12

Fig. 4.24 was prepared for comparison of the flexural behavior of different simulated cases. As demonstrated in this clustered column chart, the maximum von Mises stress of the concrete beam for the RCBeam with BFRP wrapped laminated layer was about 22% lower than that of the RCBeam. This can be attributed to the portion of the stress carried out by the BFRP layer. Also, for the beams with the web openings it can be seen that for all the cases after adding the BFRP laminate the stress level were significantly reduces. Also, the maximum stress level was related to the cases with rectangular web openings, however, this stress level for the RCBeam-R-BFRP-Wrapped condition was lower than that of the RCBeam-R.

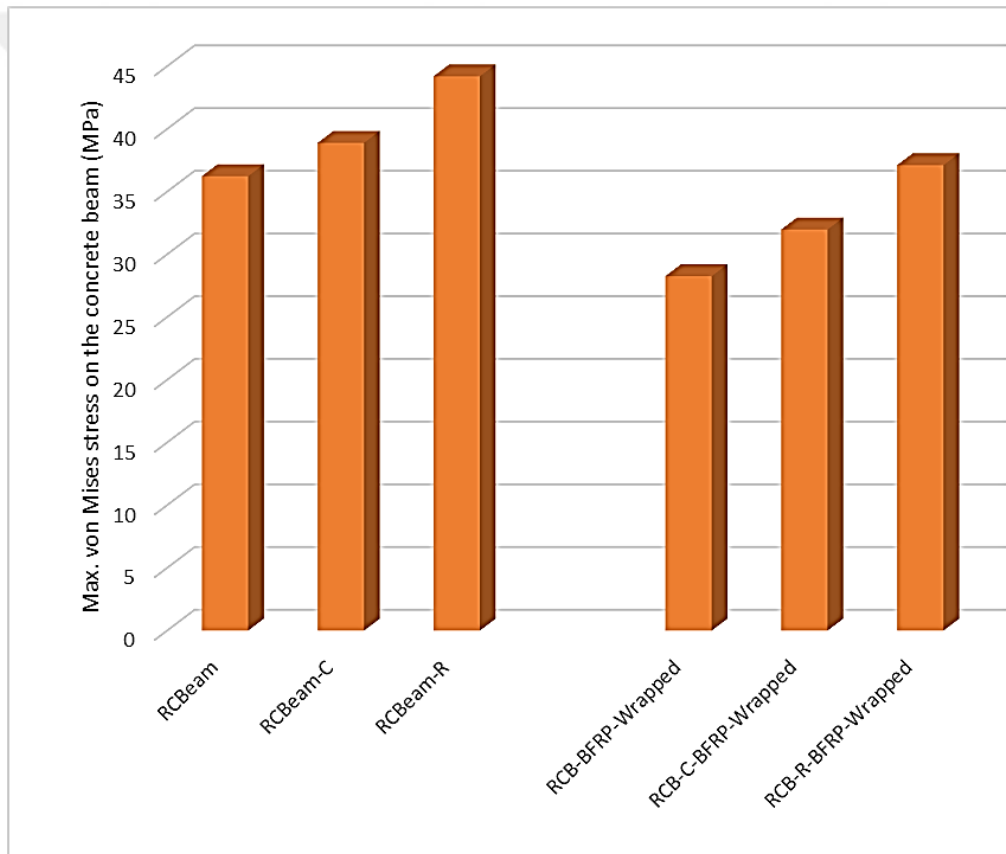


Figure 4.24. Maximum von Mises stress on the concrete beam in different cases.

5. CONCLUSIONS

The leading purpose of this thesis was modeling the beams with and without web openings to analyze the flexural behavior of the beams at different conditions. Additionally, supporting function of the BFRP wrapped layer were investigated to observe the positive effect of this layer on the flexural behavior of the beams. According to the conclusions of the simulation, the following outcomes can be listed:

- a) Considering the effect of the web openings, it was asserted that with the addition of the web openings on the RC beam the level of stress on the elements were increase significantly. For instance, for the cases without the BFRP wrapped laminates with adding the circular and rectangular web openings, the maximum von Mises stress level on the concrete beams were enhanced 8% and 22%, respectively.
- b) With comparing the outcomes of the simulation for all cases, it can be understood that BFRP decreased the level of stress on the beam at the same deflection levels due to the supporting function of the BFRP throughout the bending test.
- c) The failure behavior of the beams has been changed and stress concentration region was shifted to the center of the beam where the openings were located. Furthermore, the corner and top of the web openings were the high potential regions for the crack initiation and failure of the RC beams.

6. RECOMMENDATIONS FOR FUTURE WORKS

Although, many works have been conducted to investigate the effect of shape, size, and position of web openings on the reinforced concrete beams, there is a lack of information related to the structural behavior of the RCBs with and without FRP reinforcements which need to be studied numerically and experimentally. Some of these expected investigations are listed as follows:

- a) Shape effect of the FRPs can be investigated numerically and confirmed with experimental studies.
- b) Different types of FRPs with various thicknesses should be designed and the effect of layer thicknesses on the flexural behavior of beams can be investigated.
- c) Effect of cyclic loading on the strength of the RCBs reinforced with FRPs can be investigated to reveal the crack initiation and propagation through the cyclic flexural loading.
- d) Optimization of web opening size and shape can be done using different optimization methods with respect to flexural strength.

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