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ALTINBAS UNIVERSITY

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Civil Engineering

**FLEXURAL BEHAVIOR OF REINFORCED CONCRETE
BEAMS WITH LARGE WEB OPENING
STRENGTHENED WITH DIFFERENT KINDS OF FRP
COMPOSITE UNDER CYCLING LOAD**

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OF FRP COMPOSITE UNDER CYCLING LOAD**

by

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The thesis titled “FLEXURAL BEHAVIOR OF REINFORCED CONCRETE BEAMS WITH LARGE WEB OPENING STRENGTHENED WITH DIFFERENT KINDS OF FRP COMPOSITE UNDER CYCLING LOAD” prepared and presented by Shahlla Abbas Abulqasim was accepted as a Master of Science Thesis in Civil Engineering.

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Signature

DEDICATION

First and foremost, I dedicate this master's thesis to my mother.

I have to thanked her for her love and support throughout my life. Thank you for giving me strength to reach this level of higher education to realize my dreams...

I also dedicate this thesis to my husband and children.

They deserve my wholehearted thanks as well, for their love, patience, exceptional and unlimited support, understanding and encouragement, that boost my morale and soul when feeling down...

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Thank you, Allah for being there for me in difficult times.

This thesis is only the beginning of my journey.

ABSTRACT

FLEXURAL BEHAVIOR OF REINFORCED CONCRETE BEAMS WITH LARGE WEB OPENING STRENGTHENED WITH DIFFERENT KINDS OF FRP COMPOSITE UNDER CYCLING LOAD

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In the current thesis, the effect of different types of fiber reinforced polymers (FRPs) such as carbon fiber reinforced polymer (CFRP) and Basalt fiber reinforced polymer (BFRP) laminates on the flexural strength of reinforced concrete beams (RCBs) was investigated using numerical method. However, the main aim of the current work is modelling of the reinforced concrete beam strengthen by CFRP and BFRP laminates to investigate the supporting effect of them, the effect of web opening size was also studied under the cyclic loading. To this end, cyclic loading was applied to investigate the flexural behavior of the RCBs with and without FRPs at different web opening conditions. All beams kept the same dimensions length, breadth, and depth ($2400 \times 300 \times 200$) mm were modeled in the finite elements adopted by ABAQUS software. Steel bars have been used for both flexural strengthening and stirrups. Both four-point and three-point bending tests with was performed using cyclic loading. The flexural strength, local analysis, and ductility

of base beam and FRP reinforced beam were analyzed. The results of the simulations revealed that the CFRP and BFRP laminates enhanced the strength of the base beam significantly. Also, with the addition of the web openings the beams were failed after the lower cycles due to the stress concentration at the web region. Moreover, with increasing the size of the web opening from 40% to 60% and 75% of the beam's width, the stress concentration was increased and subsequently, the flexural strength was declined, respectively.

Keywords: Reinforced Concrete Beams, Flexural Behavior, Fiber Reinforced Polymer, Finite Element, Cyclic Loading.

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LIST OF ABBREVIATIONS

RCB	:	RC Beam
RCB-W40	:	RC Beam with web opening 40%
RCB-W60	:	RC Beam with web opening 60%
RCB-W75	:	RC Beam with web opening 75%
RCB-BFRP-U	:	RC Beam with U shape BFRP
RCB-BFRP-U-W40	:	RC Beam with U shape BFRP with web opening 40%
RCB-BFRP-U-W60	:	RC Beam with U shape BFRP with web opening 60%
RCB-BFRP-U-W75	:	RC Beam with U shape BFRP with web opening 75%
RCB-BFRP-2L	:	RC Beam with 2-layer BFRP
RCB-BFRP-2L-W40	:	RC Beam with 2-layer BFRP with web opening 40%
RCB-BFRP-2L-W60	:	RC Beam with 2-layer BFRP with web opening 60%
RCB-BFRP-2L-W75	:	RC Beam with 2-layer BFRP with web opening 75%
RCB-CFRP-U	:	RC Beam with U shape CFRP
RCB-CFRP-U-W40	:	RC Beam with U shape CFRP with web opening 40%
RCB-CFRP-U-W60	:	RC Beam with U shape CFRP with web opening 60%
RCB-CFRP-U-W75	:	RC Beam with U shape CFRP with web opening 75%
RCB-CFRP-2L	:	RC Beam with 2-layer CFRP

RCB-CFRP-2L-W40 : RC Beam with 2-layer CFRP with web opening 40%

RCB-CFRP-2L-W60 : RC Beam with 2-layer CFRP with web opening 60%

RCB-CFRP-2L-W75 : RC Beam with 2-layer CFRP with web opening 75%



LIST OF SYMBOLS

σ_c : Compressive stress

E : Elastic modulus

ε_c : Strain under compression

ε_c^{pl} : Plastic strain under compression

d_c : Compressive damage variable

σ_t : Tensile stress

ε_t : Strain under tension

ε_t^{pl} : Plastic strain under tension

d_t : Tension damage variable

C : Cohesion in the criteria of the yield strength

f : Damage factor

Ψ : Dilation Angle

μ : Viscosity

1. INTRODUCTION

In modern construction, it is necessary to create a system of pipes and ducts to provide basic services. These services are water pipes, sewerage, air conditioning, power wiring system, communications, and internet services. Typically, the ducts which have been mentioned are under the slit of the beam and, for aesthetic considerations, they are embraced with a swung roof, forming an unusable room. To optimize the design, it is conventional to use beams with web openings through which these channels can pass, and eventually, it reduces the amount of unused area and as a result, the design is more compressed. This compact design does not demonstrate great savings for usual buildings but in the case of a skyscraper, such a design can have enormous influence as it can reduce the height of the final building by the amount of saving per floor time in the number of floors. This may be one of the most important reasons why web openings have been introduced to the concrete beams [1].

This research deals with the flexural behavior of Full-scale Reinforced Concrete Beams (RCBs) under the reverse cyclic loading. The RCBs strengthened externally by different kinds of Fiber Reinforced Polymer FRP (such as Basalt BFRP, Carbon CFRP, and Glass CFRP). The RCB specimens contain a large opening (ranged from 40 to 75% of the web depth) at the flexural zone. The works divided into two parts, the first one strengthened the RCB specimens by FRP with traverse opening at the flexural zone, while the second part rehabilitation these specimens with traverse opening at the flexural zone after approaching the yield point. One solid beam without an opening and strengthening used in this work as a reference specimen. Different schemes used to strengthen the RC specimens at the flexural zone (wrapping, external surfaces without bottom surface, the bottom surface, and inclined orientation), the number of layers of FRP, and combination of FRP layers to simulate the real flexural behavior for such elements. The

obtained results from this study will be based on the experimental and Finite Element Approach (FEA).

1.1 CONCRETE BEAM

Nowadays, concrete is one of the most important and widely-used materials used in construction as well as steel. It has some noteworthy positive features such as high strength, high durability, resistance to fire. Additionally, it is very simple to use and can be prepared to fit every shape, form, and size. Four fundamental ingredients of concrete are Water, cement, sand as fine aggregate, and gravel as aka coarse aggregate. After mixing these ingredients, the formation of a binder as a result of hydration of cement leads to a hardened mass with pores. There are many types of cement with different specifications such as rapid set, low heat, and other properties [2-4].

Two main structural sections of construction are beams and columns that play an important role in carrying loads and weights and transferring them to the foundation and ground. Beams are normally horizontal fundamental parts that carry loads perpendicular to their longitudinal direction. That beam is attached to the column and this combination is termed direct support. Also, the beam combined with beam and this connection is named indirect support.

1.2 CONCRETE BEAMS WITH WEB OPENINGS

With composite dowel strips, steel girders and concrete chords can be safely and efficiently combined to form high-performance composite structures. However, important aspects of the load-bearing and deformation behavior of composite beams with composite dowel strips have not yet been clarified. This is where the present work starts [5].

In the first step, the influence of transverse openings in concrete on the punching behavior of composite dowel strips is examined. Transverse openings divide the resulting punching cones and reduce the shear stresses that can be transmitted through openings friction. This reduces the shear capacity of the composite dowel strips. In order to analyze the load-bearing mechanisms in concrete with web openings, shear tests are carried out with different openings widths and

distances. Since known design approaches for describing punching neglect the influence of transverse openings, an existing model is expanded to include the openings influence, validated on a test database, and transferred to the design level.

In the next step, the load-bearing behavior of composite dowel strips under tensile, compressive, and combined shear-tensile loads is analyzed. For the tensile and compressive strength of individual dowels and groups of dowels in concrete beams with and without web openings, design approaches are developed that are based on models for pairs of headed bolts on rigid anchor plates. The combined tensile and shear stresses of bonded dowels are recorded with an interaction model. Sufficient ductile bonding agents are required for a plastic bending design of composite beams. To describe the deformation capacity of composite dowel strips and the non-linear relationship between shear force and slip, model approaches are derived in which shear load-bearing capacity and elastic dowel stiffness are incorporated [5].

From parameter studies, constructive boundary conditions (such as concrete cover and anchor dimensions) are determined, which ensure ductile deformation behavior as EC4 (deformation capacity > 6 mm). With the anchor characteristics obtained in this way, non-linear FE simulations are used to investigate the partial anchoring of composite girders with flange-less steel girders and composite dowel strips. In parameter studies, minimum anchoring degrees are calculated for different beam spans, dowel characteristics, cross-sections, and load forms (single load, linear load). Based on this, practical approaches for minimum anchoring are formulated. Finally, the shear force load-bearing behavior of composite girders with composite dowel strips in the area of large web openings is analyzed and an engineering model for the shear force load-bearing capacity is developed, which records the failure types of failure, shear force failure of the concrete slab and composite material failure at the edge of the opening. The previously developed approaches for

the shear, tensile, and compressive behavior of composite dowel strips are incorporated into the model. The engineering model is validated in tests and converted into a practical design approach [5].

1.3 REINFORCED CONCRETE BEAMS

Ductility, or the ability of a structure or structural members to absorb and dissipate energy through post-elastic deformations, is best improved by adequate reinforcement detailing and retention at specific locations where plastic hinges can potentially develop. For the construction of a bridge or structure that is designed for gravitational loading, it is common practice to connect vertical reinforcement at the base of the quay with starter bars by projecting higher foundation bridge supports in structures or at the junction of floor slabs and columns in building structures. In the absence of adequate detention facilities, cross-linked steel [6].

Reinforced concrete beams are prone to cracking in the tension zone, which requires the need to reinforce the stretched sections with steel reinforcement. The reinforcement prevents beam fragmentation and limits crack opening. The crack formation process proceeds at a very high speed so that one can imagine it as an instantaneous rupture of the concrete in the tensioned zone, accompanied by the oscillation of the beam [7].

Reinforced concrete bending members may require reinforcement due to material decay of internal reinforcement and adjacent concrete, itinerant design and construction practices, increased service loads, and unexpected settlement and structural damage. These conditions require structural modification to increase the flexural strength of the section. One common method of increasing the flexural strength of beams, walls, and slabs is through external bonding made from fiber-reinforced polymer (FRP) slabs and sheets. FRP materials are characterized by high tensile strength and low unit weight, and they are corrosive when exposed to chloride conditions [8].

Premature rejection of external bonding of FRP plates and sheets can occur before the ultimate bending capacity to reinforce the section is reached. This is usually due to degradation of the bond between FRP and concrete or tensile peeling of the concrete coating [9].

Based on the results of experiment-based literature, the following conclusions can be drawn:

- a. The use of steel fiber reinforced concrete in the connection between the beam and the column was effective in reducing the deflection of the beam.
- b. In the case of a structural joint at a beam-column connection, the frame does not qualify as a strong frame in terms of load-bearing capacity, first crack load, rigidity and fracture structure.
- c. As a result of the use of steel fiber reinforced concrete in the connection between the beam and the column, the bearing capacity, the first crack load, stiffness and ductility have increased significantly.

1.4 FIBER REINFORCED POLYMER (FRP)

A large group of composite polymer materials is made up of reinforced plastics, in which various thermosetting and thermoplastic polymers are used as a polymer matrix, and fibrous and sheet materials are used for reinforcement from glass, polymers, basalt, carbon and other materials [10].

1.4.1 General characteristics of reinforced plastics

Reinforced plastics are widely used in aerospace engineering, various branches of mechanical engineering, construction, in the manufacture of attractions, water slides, swimming pools, sports equipment and other consumer goods. The advantages of reinforced plastics include:

- a. high strength at low density, which makes it possible to replace steel in the structures of machines and mechanisms;
- b. resistance to aggressive media, which provides products from them with long service life without the use of protective coatings;
- c. low material consumption of products made from them, which allows to reduce the weight and operating costs of mobile equipment;
- d. high manufacturability, which consists in the possibility of manufacturing large-sized products of complex shape without expensive technological tooling and equipment;
- e. the ability to regulate within a wide range of thermal and electrical conductivity, radio and translucency, depending on the type of reinforcing fibers used;
- f. the possibility of repair in "field" conditions without the use of special equipment;

- g. low capital costs for organizing the production of products from reinforced plastics.
- h. performance in a wide range of temperatures

The most widespread are reinforced polymer composites using fiberglass-based textile materials as reinforcement, which is associated with its availability, low cost, and high strength properties [11].

All the necessary raw materials for the production of fiberglass appeared in the 30s of the last century. The mass production of glass filaments and yarns became possible in 1932 when the technology for the production of glass fibers from melt was developed. Suitable binders for the production of fiberglass also appeared in the thirties of the twentieth century, when the technology for the manufacture of polyester resins was developed in the United States. Later, peroxide curing systems for these resins appeared. Since then, in principle, the raw material base has not changed, although, of course, it is still being improved and the creation of new resins, and new hardeners, and new glass materials [10].

The increased requirements for reinforced materials led to the use of first carbon and later organic high-modulus fibers of the SVM and Kevlar type in polymer composites. This was required by the creation of modern rocket-space and aviation technology, the need to reduce its mass and at the same time increase its strength and endurance, as well as ensure special technical properties.

Along with the development of new materials, the technologies of manufacturing products from reinforced composite materials were also improved. If the first fiberglass products were made by laying on a piece of fiberglass impregnated with a composition containing a resin and a hardener, then later equipment and technologies appeared that made it possible to continuously spray all the components of the composition onto the technological equipment - both chopped fiberglass, resin, and hardener - simultaneously in a given ratio. This, of course, dramatically increased labor productivity, improved sanitary and hygienic conditions, reduced the cost of fiberglass products and made it possible to switch to the serial production of large-sized items made from them [12].

Later, even more advanced, high-performance technologies were developed, which made it possible to obtain products with high aesthetic properties and less production waste by means of winding, pultrusion, injection into a closed mold, etc.

Thus, the needs of industry for more advanced materials and technologies on the one hand, and the opportunities that arose when creating new raw materials and equipment on the other hand, contributed to the expansion of the use of reinforced plastics in various sectors of the economy.

1.4.2 Structure and properties of reinforced plastics

It is customary to refer to reinforced composites materials of artificial origin of complex composition, having at least two continuous phases with a common interface. One of the phases is called a matrix, it is responsible for the shape of the product, the resistance of the composite to the effects of various aggressive media, heat and frost resistance, impact strength and other properties.

The binder should not be confused with the matrix. A binder is a polymer base from which, after appropriate processing, a matrix is formed. Important characteristics of the binder are technological: viscosity, wetting ability, survivability, etc [12].

The second mandatory phase of the composite material is a reinforcing filler, the particles of which must have a length not less than the critical length, at which the fiber strength can be realized. The critical length of a fiber depends on its diameter, tensile strength, and shear strength. An important role in the formation of the properties of the composite material is played by the interphase layer at the interface between the matrix and the reinforcing phase.

The interphase layer has both a composition and a structure that differ from the composition and structure of the matrix, since in addition to the material of the matrix itself, it also includes some products that are part of the reinforcing filler. The interphase layer is inhomogeneous in composition, and its thickness cannot be precisely determined, since the composition and structure of the boundary layer do not change abruptly. Nevertheless, the thickness of the interfacial layer is determined experimentally and by calculation, taking for it such its length, at which its composition and properties change in relation to the matrix and the reinforcing fiber within specified limits.

The thickness of the interfacial layer for various materials varies within significant limits: from 0.01 to 5 microns. Its role in the formation of the properties of the polymer composite is great, and therefore great importance is attached to the study and control of the processes of formation of the interphase layer.



1.4.3 Thermoplastics and thermosets are used as bonding materials for polymer reinforced plastics.

Resin type	Characteristics	Limitations
Epoxy	Excellent composite properties Very good chemical resistance Good thermal properties Very good electrical properties Low shrinkage on curing Can be B-staged (prepreg)	Long cure cycles Best properties obtained only with cure at elevated temperature Skin sensitiser
Phenolic	Very good thermal properties Good fire properties (self-extinguishing) B-stage possible Good electrical properties	Colour limitation Alkali resistance Contact with foodstuffs
Polyester	Wide choice of resins – easy use Cure at room temperature and elevated temperature Very good composite properties Good chemical resistance Good electrical properties	Emission of styrene Shrinkage on curing Flammability No B-stage possible
Polyimide and polyamide-imide	Excellent thermal properties Good composite properties Good electrical properties Good fire properties	Restricted choice of colour Arc resistance Acid and alkali resistance
Polyurethane	Good composite properties Very good chemical resistance Very high toughness (impact) Good abrasion resistance	Nature of isocyanate curing agents Colour Anhydrous curing No B-stage
Silicone	Very good thermal properties Excellent chemical resistance Very good electrical properties Resistant to hydrolysis and oxidation Good fire properties (self-extinguishing) Non-toxic	Lack of adhesion Long cure cycles Can only be cured at elevated temperature
Vinyl ester	Good fatigue resistance Excellent composite properties Very good chemical resistance Good toughness	Emission of styrene Shrinkage on curing Flammability No B-stage

Figure 1.1. Usual resins used as a reinforcement material in FRPs: Characteristics and Limitations (handbook)

Thermoplastics - polyamides, polyimides, polypropylene, polysulfide and others - have a high viscosity (they are solid at room temperature). Impregnation of reinforcing fibrous materials with thermoplastic binders is possible only after transferring them to a viscous-flow state.

At the same time, the use of thermoplastics as binders in the production of reinforced plastics has important advantages. First, when using them, toxic gaseous products are practically not emitted into the working area, as is the case when using oligomeric binders. And secondly, the wastes from the production of reinforced plastics based on thermoplastics are easy to dispose of, just like other thermoplastic polymers, since their macromolecules are not chemically linked [12].

Of particular interest is the possibility of obtaining, on the basis of thermoplastics, "ultimately reinforced" plastics with a reinforcing fiber content of up to 100%. Such reinforced composites are produced by reflowing a portion of the polymer fibers while heating.

Reinforced composites based on thermoplastic matrix have low residual stress and high toughness (more than $600 \text{ kJ} / \text{m}^2$), frost and thermal stability (they can operate at temperatures ranging from -60 to $+250^\circ \text{C}$) and other important performance characteristics.

Blanks for the manufacture of products from reinforced thermoplastics have an almost unlimited shelf life, which simplifies the organization of the technological process for the production of products from them.

One of the promising technologies for the production of reinforced plastics based on thermoplastics is the production of woven fabrics from a mixture of fibers, some of which melt during the molding of the product and bind the remaining unmelted fibers. The latter play the role of a reinforcing filler. Semi-finished products from such blended fabrics have a uniform structure and a constant raw material composition. The production of products from mixed fabrics is easily mechanized and can be carried out on conventional hydraulic presses.

Recently developed technologies for the production of reinforced composite materials based on thermoplastic binders, as well as technologies for molding products from mixed textile semi-finished products, create the preconditions for their wider use in the production of mass-market products.

1.4.4 Types of reinforcing fillers

Despite the fact that the theoretical strength of polymers is ~ 19000 MPa, their real strength does not exceed 100-200 MPa, which is associated with a large number of defects in their structure. At the same time, the strength of some, including high-modulus polymer, glass, carbon and other fibers is 4000-5000 MPa, and some are even higher. Therefore, for the production of high-strength polymer composites, reinforcing organic and inorganic fibers, as well as textile materials based on them, are widely used [12].

Reinforcing fillers based on glass fibers are most widely used to obtain polymer composite materials. The chemical composition of glass affects the properties of the fiber and ultimately the properties of composite materials. The basis of glasses used for the production of fibers are oxides of silicon, aluminum, magnesium, calcium. In addition, to achieve special properties, oxides of boron, sodium, zirconium, etc. are added to the glass mass in small amounts.

The strength of glass fibers is highly dependent on the moisture adsorbed on their surface. The adsorbed moisture reduces the surface energy of the fibers, causes swelling of the surface layers, leads to the development of microcracks, ultimately reducing the strength of the fibers. Drying and removing moisture from the surface of the fibers makes it possible to increase their strength, but complete desorption of surface moisture cannot be achieved even with prolonged and deep vacuum.

The use of carbon fibers to obtain polymer composite materials made it possible to solve a number of new technical problems, which is associated with the unique properties of carbon-based reinforcing materials. So, carbon fibers have high strength characteristics, low density, thermal and electrical conductivity, chemical resistance, low temperature coefficient of linear expansion, high resistance to ionizing radiation, low coefficient of friction, etc.

1.5 FRP REINFORCED CONCRETE

In recent years, damage to structural elements such as bridges, buildings due to insufficient structures (material failure or aging, poor repair and maintenance, earthquakes) has led to several methods to strengthen the construction of Different to be used. The use of FRP with their excellent mechanical properties for the reinforcement of reinforced concrete structures is one of them. Over the past two decades, the benefits of FRP reinforcement in terms of time and cost have become apparent. However, extensive studies have been conducted to investigate, in particular, the performance of reinforced concrete beams reinforced by FRP boards. FRP composites are made of high tensile fibers embedded in an epoxy matrix, they increase corrosion resistance, low weight, high weight to strength ratio, mechanical strength. This is a quick and economical way to rebuild or repair beams, columns or slabs, and surface preparation is important to achieve a successful FRP and concrete reinforcement. Therefore, the efficiency and quality of the connection between FRP and concrete composites play a major role in the transfer of stress between concrete structures and FRP plates with external bonding.

The properties of the fiber matrix material along with the properties of the concrete substrate such as roughness, strength, cleanliness of the concrete surface may also affect the quality or reliability of the joint. Epoxy resins are mostly chosen for their bonding to each other due to their high adhesion to FRP and concrete.

Over the past few decades, the reinforcement of concrete structural elements by FRP fibers has become a widely used method where high strength is required to carry heavy loads or repair due to fatigue cracking, failure modes or corrosion. This method eliminates or reduces the growth rate of the crack, delays the initial crack, reduces the hardness and increases the fatigue life of the concrete beam. The best reinforcement option in this case is FRP fiber reinforced polymer.

One of the applications of FRP is flexural reinforcement of beams or concrete slabs in long spans and if the initial design of the member is unsuitable, it can be used with FRP fibers to increase the stiffness and flexural strength and also if the number of flexural reinforcements in If the beam is less than required, flexural cracks are created under the concrete beam, which are created vertically and in the direction of bending. FRP fibers can be used to increase the flexural strength and

stiffness. Due to their low thickness and high modulus of elasticity, these fibers increase the stiffness of concrete beams and reduce their swelling.

For shear reinforcement of beams, FRP fibers are usually attached obliquely or vertically (perpendicular to the direction of shear cracks) to the sides of the beam. The lower the angle between the fibers perpendicular to the shear cracks, the greater their effect on increasing the shear strength of concrete beams. FRP fibers used for shear reinforcement of concrete beams can be U-shaped or completely around the concrete beam.

Reinforced concrete members, such as beams and columns, may be reinforced in bending due to the use of FRP composites attached to their tensile regions in the direction of the fibers parallel to the high tensile stresses (member axis). This concept is shown below.

One of the applications of fiber reinforced polymers (FRP) is the flexural reinforcement of concrete beams or slabs in long spans. Of course, this does not mean that FRP cannot be used on beams and slabs with small openings.

If the initial design of the member is unsuitable, the rigidity and flexural strength can be increased by using FRP fibers. If the ratio of thickness and height of the member to its opening is low, its stiffness is low and as a result, it rises in the middle of the opening of the member (beam or slab). Also, if the amount of bending reinforcement in the beam or slab is less than required, bending cracks will form under the beam or slab. These cracks are vertical and are created in the direction of bending (perpendicular to the direction of longitudinal reinforcements) at the place of maximum bending anchor.

To increase the stiffness and flexural strength, carbon polymer sheets (CFRP) can be bonded to the flexural member with epoxy adhesive. As a result, the middle of the beam of polymer sheets should be glued to the bottom and the support of these sheets should be glued to the top. The direction of the fibers should be in the direction of steel reinforcements because the stiffness and tensile strength of the fibers in that direction are the highest. Despite the low thickness of polymer fibers, they have a high modulus of elasticity that increases the stiffness of the beam or slab and thus decreases its swelling.

Reinforcement of flexural members with FRP fibers is very important. This method of reinforcement is used in various structures. For example, FRP flexural reinforcement method is commonly used for reinforcement of stair decks, beams of residential buildings, slabs of buildings.

1.5.1 Shear reinforcement using polymer fibers (FRP)

In concrete beams, the joints, which are located in the direction perpendicular to the direction of the beam, play the role of providing its shear strength. As we know, due to the low shear strength of concrete, hammer is used to provide sufficient shear strength in beams. If the beam does not have sufficient shear strength, the shear cracks will form obliquely at an angle of about 45 degrees to the abutment at the maximum shear location. To shear the beams, the polymer fibers (FRP) are usually attached to the sides of the beam obliquely or vertically (perpendicular to the direction of the shear cracks). The lower the angle between the fibers perpendicular to the shear cracks, the greater their effect on increasing the shear strength of the beam. FRP strips used to strengthen the shear of the beam can be U-shaped or completely cover the beam.

1.5.2 Surface reinforcement using FRP reinforcements

FRP sheets that are glued to the surface of concrete members to strengthen the concrete member are vulnerable to impact, heat, fire and ultraviolet rays. To prevent these damages, the surface reinforcement method or the Near-surface mounted (NSM) FRP reinforcement method can be used.

In this method, cracks with a depth less than the thickness of the concrete cover are created on the concrete surface of the member and carbon polymer reinforcement (CFRP) or glass polymer reinforcement (GFRP) are glued inside these gaps. In this method, a suitable surface is created between GFRP and CFRP reinforcements and the member.

1.5.3 Reinforcement of concrete beams with FRP

Reinforcement of concrete beams with FRP to achieve the desired performance by increasing the bearing capacity of bending and shear, increase the wear resistance, increase the resistance to corrosion and even heat. FRP materials can also be used to reinforce concrete beams with FRP whose reinforcement has been corroded due to adverse conditions. Thus, concrete beams, while

increasing flexural and shear strength, are also protected against corrosive environmental conditions by using FRP.

Reinforcement of concrete beams with FRP and reinforcement of concrete beams with FRP is a relatively new method that is used in seismic improvement projects. FRP materials have very good physical properties, which can be referred to as high tensile strength, thickness and low weight. In general, reinforcement and reinforcement of concrete beams with FRP to increase its seismic performance is through increasing the bearing capacity of flexural, shear, increase of abrasion resistance, increase of corrosion resistance and even heat. There are several methods to eliminate the weakness of the beam, including the method of reinforcing concrete beams with FRP due to its very high advantages. In fact, reinforcing concrete beams with FRP is an economical and effective solution to strengthen concrete beams against bending and cutting, which has become very common today due to the reduction of FRP prices. During the reinforcement of concrete beams with FRP, FRP materials and fibers reach 3 times the tensile strength of steel in 3-4 days, therefore, due to the fact that FRP fibers have a very high tensile strength compared to steel sheets, the connection of FRP to The tensile area of the concrete in the concrete beam will increase the bending capacity of the section. Numerous factors such as cross-sectional dimensions of concrete beams, area and mechanical characteristics of existing rebar's and FRP used, as well as the strength of existing concrete, are involved in increasing the flexural strength of concrete structures using FRP systems. In the technical literature, this increase in resistance has been reported from 10 to 160 percent. Therefore, according to the existing restrictions on ductility, operation criteria and other regulatory restrictions, increasing the flexural strength of concrete structures up to a maximum of 40% is considered acceptable and recommended. Also in reinforcing concrete beams with FRP by connecting FRP materials to the tensile area of concrete so that the direction of its fibers is perpendicular to the longitudinal axis of the beam, increases the shear strength of the beam.

The results show that the hardness of FRP-reinforced concrete beams after cracking is much higher than the hardness of unreinforced beams after cracking, which is very important during an earthquake. FRP sheets and laminates, due to their small thickness (about 0.05 inches or 1.3 mm), make the beam stronger with the least increase in beam dimensions.

1.5.4 CFRP

In recent years, the reinforcement of existing structures has become increasingly important. Various reasons have led to the deterioration of structures, increased design and execution errors are among these factors. In addition, many existing structures need to increase strength due to increased loads [13].

From an environmental and economic point of view, repairing, repairing, strengthening, and strengthening existing structures is preferable to demolishing and rebuilding structures. Also, in many cases, retrofitting structures is less expensive and less troublesome than renovating them. In addition, the speed of reinforcement is faster than the renovation, which causes the structure to be out of service for a long time [13].

Recent advances in the reinforcement industry include the use of fiber reinforced polymer (FRP) reinforcing coatings for the reinforcement of concrete, steel, masonry and even wood structures. Acceptance of the FRP system reinforcement method is closely related to the level of trust of structural engineers, officials and employers in this method. Adequate trust can be gained through standardized tests and a better understanding of the behavior of FRP-reinforced structures in a variety of conditions. A correct understanding of the structure's behavior under normal conditions, high temperature and low temperature, is essential for accepting this method

In 2003, a committee was formed to review research needs in the field of FRP materials for the reinforcement of concrete structures. These studies have shown that the "durability" and "fire resistance" of FRP systems need serious consideration. One of the "durability" aspects of these studies, which is closely related to fire resistance, is the effect of high temperature on the behavior of FRP-reinforced structures.

In another study to identify and prioritize important information related to the durability of FRP sheets and rebars, it was found that information available on FRP-reinforced structures when exposed to high temperatures or ice cycles and melt fall, very little.

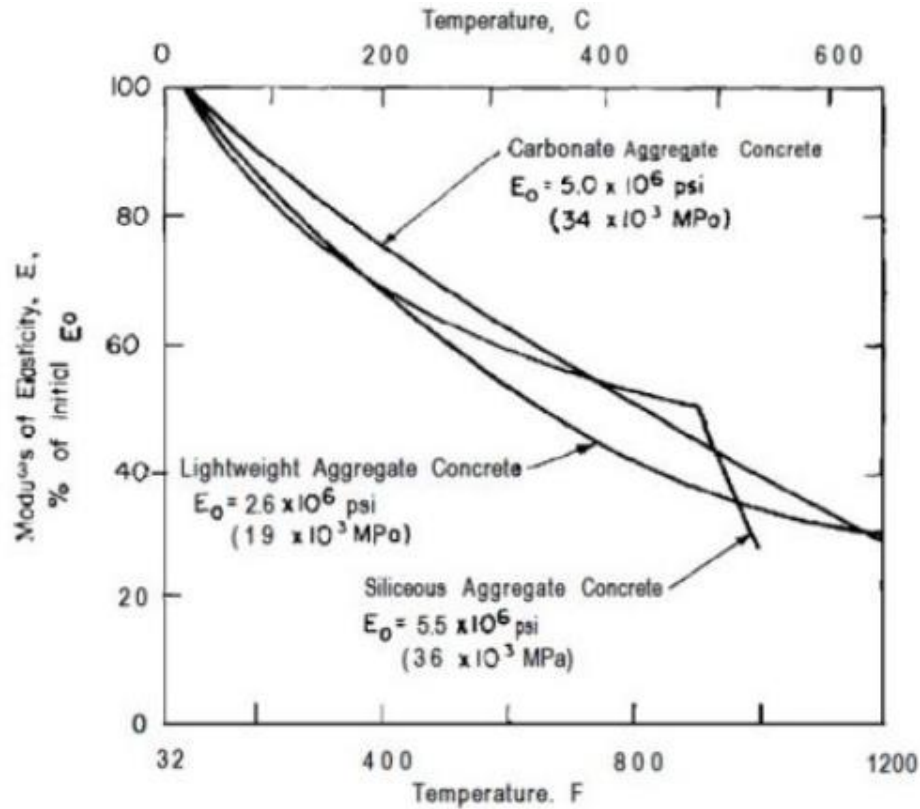


Figure 1.2. Heat impact on concrete's Young Module

The effect of fire on structures reinforced with FRP has been mentioned in literature in which this parameter is considered as a special load in which the contribution of FRP in resistance is considered insignificant. This means that after the absence of FRP, the structure must be able to withstand the loads with the desired safety coefficients (load and material coefficients). This is believed to prevent the sudden collapse of the FRP-reinforced structure after the adhesion between the concrete and the FR has disappeared (for example, during a fire or vandalism).

These proposals limit the maximum amount of resistance obtained to the difference between the safety coefficients related to the specific load combination and the final load combination. Studies have shown that the adhesion between the concrete and the FRP layer disappears near or above the glass transition temperature of the adhesive, T_g . The behavior of reinforcing FRPs can be affected by temperature changes in the operating environment, due to the large differences between the thermal expansion coefficients of concrete and FRP. This difference causes thermal stresses at the FRP joint with adhesive and adhesive with concrete, which affects the behavior of the structure.

In addition, the characteristics of different phases of concrete, adhesive, FRP and the boundary between them are affected. It is said that increasing the temperature has certain negative effects on the existing adhesive, even at temperatures lower than the glass transition temperature of the adhesive.

1.5.5 BFRP

There are many advantages and some disadvantages of employing BFRP reinforcements in the reinforced concrete beams [14-18]. Some of these are as following:

Advantages:

- a. Low weight
- b. It can decrease the overall weight of the structure after reduction of concrete dimensions and covering the sides of concrete.
- c. It is corrosion resistant and can be attached to the surface.
- d. High initial tensile strength of BFRP.

Disadvantages:

- a. The modulus of elasticity for BFRP is low.
- b. The design and attachment should be design carefully.
- c. It's different with the conventional reinforcement materials such as steel, therefore there is a lack of information about the structural behavior.

1.6 FLEXURAL BEHAVIOR

Applying force or coupling to a beam causes tension and strain in its internal parts. In order to determine these stresses and strains, we must first obtain the internal forces and couplings applied to the beam sections. To learn how to determine these internal committees, consider the following figure. This figure shows an all-inclusive AB beam whose free end is exposed to a concentrated force P [19].

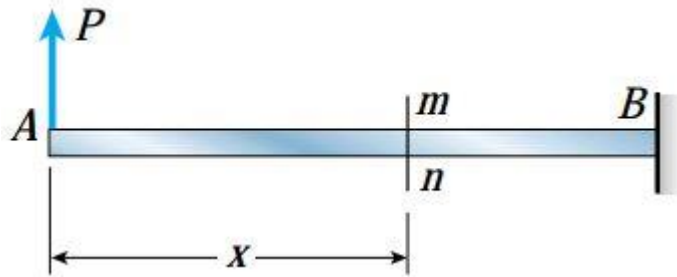


Figure 1.3 Schematics of a beam

By making a cut at a distance x from the free end of the beam (cross section mn in the figure 3) we can draw the free body diagrams of the two sections created. Due to the force P and the stresses applied to the cross section mn , the free body diagrams will be in equilibrium. These stresses show the interaction between the left and right parts of the beam. At this stage of the analysis, it is not clear how the stresses applied to mn are distributed. However, we know that the result of these stresses must be such that the free body remains in equilibrium.

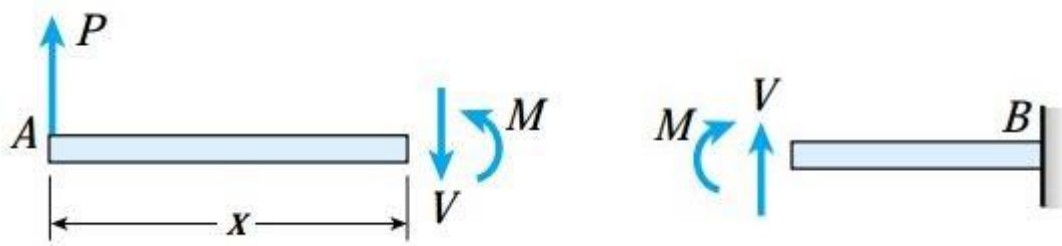


Figure 1.4 Shear force V and flexural torque M in the free body diagram of a beam

Using static rules, we can decompose the result of stresses applied to the cross section into a shear stress (V) and a flexural torque (M). Due to the transverse load P on the axis of the beam, there will be no axial force (along the horizontal axis) on the cross section of mn . The shear force and flexural torque are located in the plane containing the beam (longitudinal section). Hence, the shear force vector in this plane and the bending moment vector perpendicular to it are applied.

Shear forces and flexural moments such as axial forces within the bars and torsional moments within the shafts are the result of stresses distributed across the cross section. For this reason, these committees are collectively known as "Stress Resultants". The stress outcomes of certain static beams can only be calculated using equilibrium equations.

2. LITERATURE REVIEW

Recently the application of fiber-reinforced polymers (FRPs) in civil engineering has risen noticeably due to various advantages of these materials such as low density, high strength to weight ratio, flexibility, comparatively low cost, appropriate durability, and corrosion resistance compared to traditional materials. In the last two decades, the usage of FRP materials for the strengthening of reinforced concrete (RC) has attracted notable attention. Therefore, there have been many studies conducted on the mechanical behavior such as compression, flexural, fatigue, etc. of strengthened sections by FRP [20, 21].

The flexural behavior of reinforced concrete (RC) beams has been studied widely [22-24]. The results of these investigations have revealed the influence of several methods of the FRP system to obtain the needed outcomes. Numerous numerical and experimental studies investigated the effect of different types of strengthening methods in FRP reinforced beams. They have studied different types of FRP materials such as glass, Basalt, carbon, and aramid as well as various shapes of the combination of FRP to the RCs [9, 25-28].

Sonnenschein et al. [29] have investigated the effect of using different FRP composites in the bridge constructions. They reviewed many studies and suggested that steel reinforcement can be substituted with FRP composites specifically when concrete structures subjected to natural environment. They specified that corrosion is the main reason of the failure for the steel reinforcement beams and columns of the bridges, so in these structures FRP can completely satisfied the requirements as a reinforcement instead of traditional reinforcement (steel). They reported the mechanical properties of various types of FRPs and their application in different structural elements of bridges.

De Lorenzis et al. [30] compared the behavior of full-scale supported highway bridge deck panels reinforced when bending with either externally bonded CFRP laminates or internally placed NSM CFRP bars. The failure of CFRP laminate reinforced deck covers lies through a combination of tearing and peeling CFRP laminates. NSM CFRP service has been filed tensile rupture of CFRP bars. With respect to the ability to unstrengthen deck control, the torque increases from 17 to 29%, the decks are reported to be fitted with externally bonded CFRP laminates and internally placed NSM CFRP bars, respectively.

They tested four reinforced concrete T beams with NSM glass FRP (GFRP) and NSM carbon fiber reinforced plastic bars. The retrofitted CFRP beams experienced an increase in strength of 30% (two No. 3 CFRP bars) and 44% (two No. 4 CFRP bars) compared to the unstrengthened control specimen. CFRP reinforced beams have failed due to debonding of the NSM rods. The specimen reinforced with two No. 4 GFRP bars also failed for debonding on the NSM GFRP bars at 26% higher load than the control specimen. The authors reported that communication is critical to using this technology effectively. Bond failure of NSM FRP bars, also identified by De Lorenzis et al. [30], need further study. Loss of adhesion on NSM FRP bars due to epoxy cleavage is used to hold the rod in place in the post. It has been suggested that this failure of the state limit could have been avoided by lengthening or anchoring NSM rods in the flange. Remarkably, the authors reported that if debonding on NSM FRP bars is to be prevented, splitting of the concrete surrounding longitudinal steel bars may become the state's control limit.

Loss of fastening was noted in several of their test specimens. In this regard, experimental studies of the bond, De Lorenzis et al. [31] in another investigation argue that epoxy is superior to cement paste as the groove of the filler material, thread size up to 2.0 bar is optimal, and a smooth surface gives the groove a little lower, local strong bonds, but preferable because it gives a more plastic behavior of bond slip.

Taljsten and Caroline [32] estimate four rectangular concrete beams subjected to four bending points and monotonically loaded in deformation control. Four test beams were reinforced with NSM CFRP strips and the fourth served as a control. Two of the three reinforced the joists designed for bonding with epoxy FRP and the third use cement mortar. The test results showed that two of the three retrofitted beams failed due to loss of anchorage between the NSM FRP strips and the concrete. The third reinforced the beam fell through due to the tensile rupture of the FRP strip. The load forecast is measured by the failure of the overestimated strength.

Rizkalla et al. [33] compared beams reinforced on an equal basis with axial stiffness using NSM FRP bars and strips and outside bonded FRP laminates. Their research showed that higher tensile strength and increased ductility were achieved by NSM to strengthen specimens. They also noted that the integrity link for NSM FRP bars was found to be less effective than for NSM FRP bars. Taken together, these research results indicate that the relationship of integrity cannot be taken for granted and that the relationship of related limit states should also be addressed in the NSM FRP.

DeLorenzis and Nanni [34] show that contract performance guarantees will depend on several factors including bond length, NSM FRP bar surface diameter characteristics, material characteristics of FRP geometry rhythms, and properties of epoxy seams. Their experimental tests showed three linkage related failure modes, namely, cleavage of epoxy coatings, cracking of concrete surrounding groove, and NSM FRP rod withdrawal.

Harajli and Rteil [35] evaluated the retention effect using carbon FRP (CFRP) jackets on the seismic performance of rectangular RC columns, where the reinforcement columns are spliced into column moving areas. It was found that the content of the junction zone with a relatively thin FRP jacket reduced bond degradation, which significantly increased the energy absorption and dissipative capacity of the columns, and resulted in a significant increase in seismic performance compared to unconfined columns. Corresponding improvements, mainly due to improved performance of the splicing bond reinforcement column as a result of FRP confinement.

Harris et al. (2006) investigated the use of a CFRP jacket for seismic retrofitting of nonductile columns that have insufficient splice at the knees. It was found that with a CFRP jacketed retrofitting, the rated bending power of the columns could be achieved. Although increased viscosity can be achieved, they are limited by the potential for slippage, which has proven to be independent of the holding effect of the CFRP jacket.

Recently, Gosha and Sheikh [36] have tested building columns with spliced reinforcement retrofitted for seismic loads using external CFRP jackets. It was found that the CFRP retrofit method improved the seismic resistance of the column and resulted in more stable hysteresis behavior and less stiffness and strength degradation compared to unretrofitted columns.

Rhine and Mark (2016) defined minimum amount of shear reinforcement trying to ensure ductile load-bearing behavior of reinforced concrete beams while at the same time adhering to structural rules. If the required amount of reinforcement is not met, however, brittle failure does not necessarily have to occur. Depending on the position and amount of the existing reinforcement, the influence of other bearing components as well as the crack formation, it is possible to take over the crack load, including a subsequent load increase and sensible shear crack width restrictions. This is helpful for evaluating existing structures with weak shear force reinforcement as "sufficiently ductile". In beam tests on reinforced concrete components with weak shear force

reinforcement, structural and deformation behaviors are analyzed, taking into account the critical failure crack and the structural implementation, and evaluated with regard to the minimum amount of shear force reinforcement required. The shear resistance as well as the ironing effectiveness in the identified effective shear range are examined and tips for practical implementation are derived. On minimum shear reinforcement amounts for reinforced concrete beams A ductile shear bearing behavior of reinforced concrete beams is recently ensured by providing standardized amounts of minimum shear reinforcement in compliance with established detailing provisions. However, lower than minimum shear reinforcement amounts do not necessarily go along with a brittle mode of failure in all cases. Depending on the individual layout and amount of stirrups, the contributions of other bearing capacities and the crack formation itself, the initial cracking force might be overtaken even along with further load gains and reasonable limited shear crack widths. Especially the latter one holds potential to rate the failure mode - brittle or ductile - on site. Experiments on lightly shear reinforced single span concrete beams are evaluated and rated with respect to minimum shear reinforcement amounts required. Thereby, special interest is set on the load-deformation response obeying the critical shear crack and the structural design. Finally, the overall shear resistance as well as the stirrups' efficiency in the effective shear domain are analyzed to derive suggestions for future practical application.

Later in 2018 C. Rhine [37] investigated the load bearing behavior of the RC beams and his results were in complete agreement with his previous papers. A ductile shear force behavior should be ensured by a minimum reinforcement and compliance with design rules. If the amount of reinforcement required is not met, this does not necessarily result in a brittle failure. From the analysis of the critical shear crack, the component resistance is examined via the effectiveness of the stirrups in the identified effective shear area and recommendations for the computational consideration are derived. A combination of criteria is recommended to assess the type of failure that occurs. The realistic values of concrete and additive reinforcement load should be put in relation to each other. Since the ductility also depends on the number of activated stirrups, there should be sensibly limited bar spacings. Irreversible steel expansions are to be avoided and are excluded by limiting the width of the crack. In addition, the failure can be characterized by the expansion rate of the failure crack.

Shafiq et al. investigated 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 results 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 presence 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 et al. [38] investigated the "effect of shape and opening location on the structural strength of deep reinforced concrete beams with opening". In this study, the effects of the shape and location of the opening on the structural behavior of deep reinforced concrete beams with opening, by keeping the size of the opening constant. In this study, finite element software was used to perform nonlinear finite element analysis. The final strength obtained from the finite element software of reinforced concrete deep beam with opening showed less than 20% difference compared to the laboratory results. This study showed that the opening location has a greater effect on the structural strength than the opening shape, so that the location of the openings near the upper corners of the deep beam can double the strength. Also, the narrow rectangular opening (with the direction of length in the horizontal direction) reduces the structural strength of the deep beam by 40% less compared to the large rectangular opening.

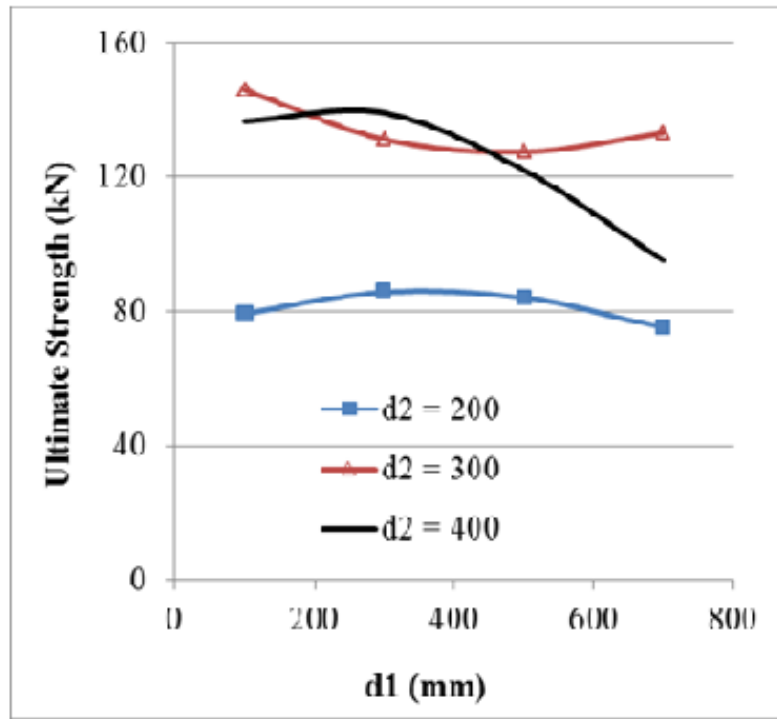


Figure 2.1 Maximum strength of the beam with a circular opening

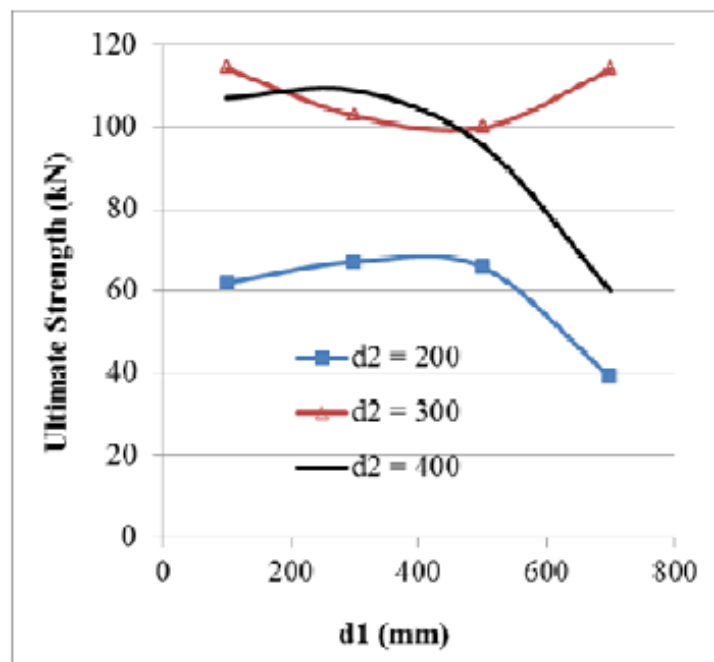


Figure 2.2 Maximum strength of the beam with a rectangular opening

F. Rahimi [39] investigated FRP utilized finite element models for modeling deep beams with apertures that were reinforced with strips. Since the regulations did not explicitly mention the analysis and design of deep-opening beams, truss models are skeptical about the design of these specimens; Therefore, finite element models can be a good option for the behavior of these beams. The central opening used did not interrupt the load transfer path; While in the samples of two openings, the path of the handles was cut by the openings and reduced the shear capacity of deep beams.

Comparison between laboratory results and finite element data with the results of the regulations shows the accuracy of the modeling performed on the reinforced and non-reinforced deep beam specimens. The results of parametric analysis show that ACI that the wider the openings cut the path of the handles, the more the shear strength decreases and the specimens that were reinforced in the direction perpendicular to the plastic strain vectors had higher shear strength. She concluded that deep beam rupture is mainly caused by shear. In order to strengthen and improve these beams, polymer tapes have been attached to the depth of deep concrete beams and the extent of improvement of the behavior of these beams has been investigated.

For this purpose, numerical modeling of these beams was performed using Abacus finite element software. Due to the fact that in this dissertation numerical models consisted of two groups, the first group was referred to as deep concrete beams with one opening in the core and the second group was referred to as the models with double opening in the core. The final results of numerical analysis of both groups are presented separately.

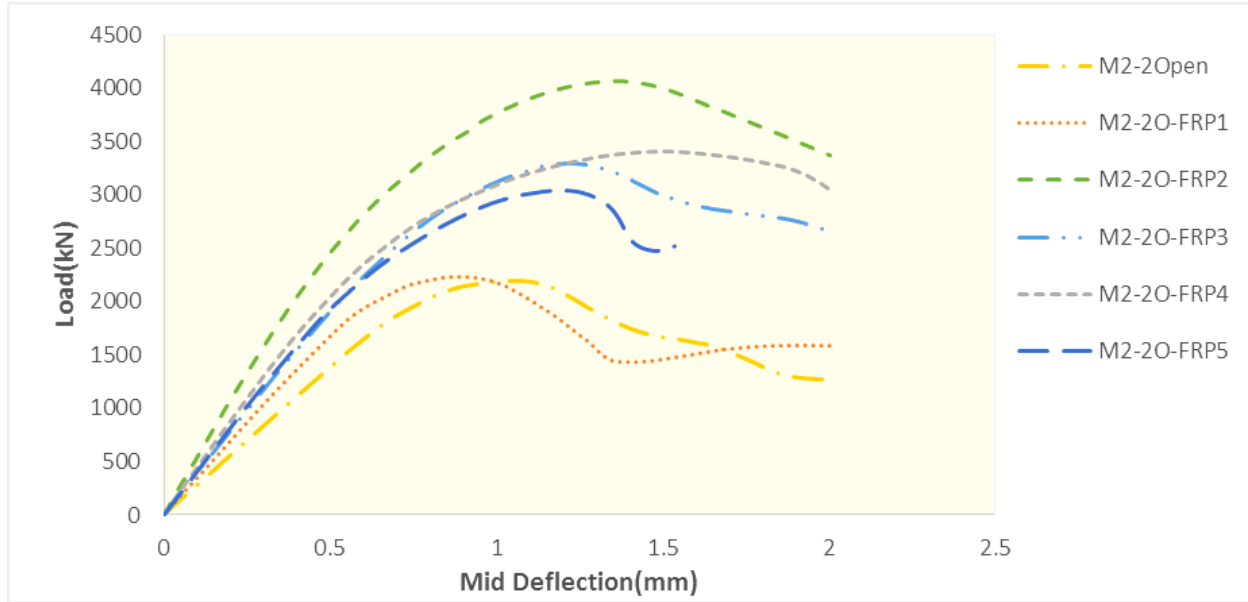


Figure 2.3 Load - displacement diagram for deep concrete beams without opening and reinforced with different arrangement of FRP strips [39].

Hawileh et al. [28] in their paper which was a numerical study on composite reinforced concrete beams with openings designed 12 nonlinear finite element samples and investigated the performance of two different group of reinforced concrete beams both with openings and first group of samples was strengthened by CFRP in the opening region but the 2nd group wasn't strengthened. Hawlieh's team used El-maaddawy's data as the main reference and their simulations were in complete agreement with El-maaddawy's findings.

Their team studied the interfacial interaction of CFRP layers with the concrete. This study was mainly on the crack initiation and propagation, which eventually, proved to be as accurate as possible since their predictions was fairly as expected based on experimental results. In addition to the crack pattern investigation, Hawileh's simulations provided loads deflection diagrams which successfully recreated the experimental results. Their error in predicting failure load was only 3.2%, while this number in case of strains was a few percent higher. As it has been observed in respective experiments, CFRP shear strengthening had enormous impact on the load bearing of RC beams as this number for CFRP strengthened FE models was about 70% higher than unstrengthened ones.

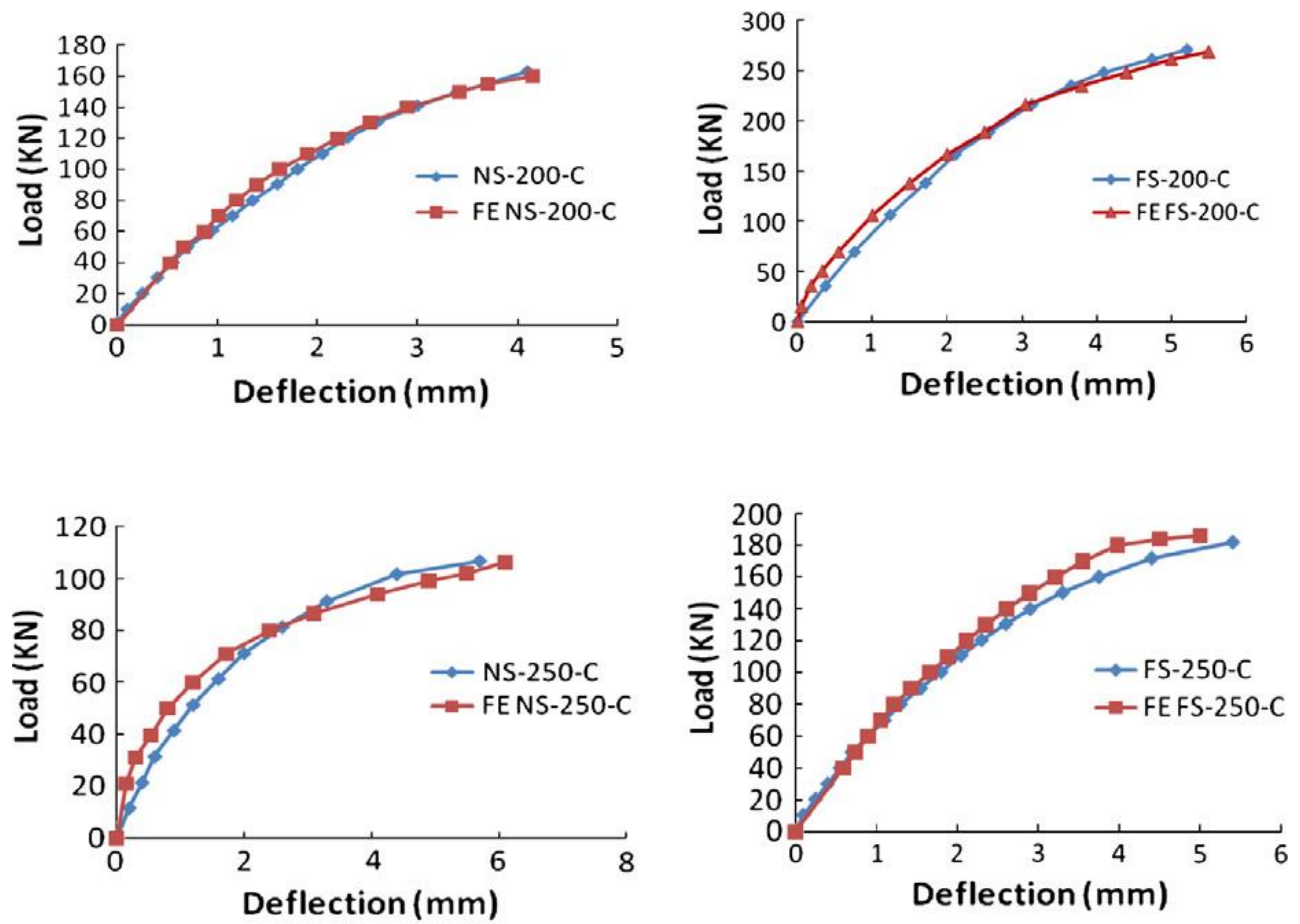


Figure 2.4 Comparison between Load-Deflection curves of experimental samples and finite element models.

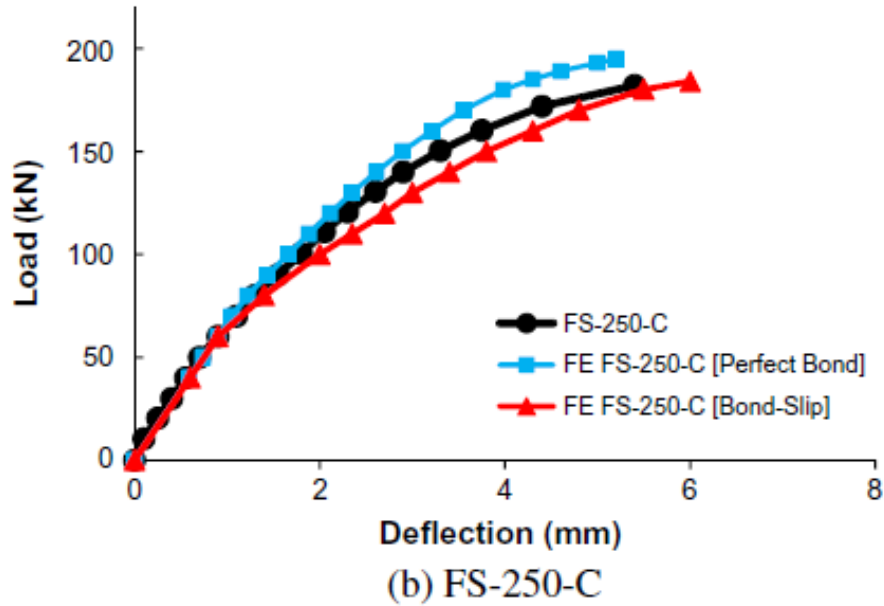


Figure 2.5 Effect of interfacial bond-slip model on FE load-deflection response.

R. Salih et al. [40] have investigated the effect of adding CFRP to the beam with circular web opening. They have studied the flexural behavior of the beam both experimentally and numerically using ABAQUS software. They have stated that their results revealed that different parameters such as beam capacity, degradation of stiffness, various failure modes, and energy absorption may be affected by adding web openings on the flexural region.

They proved that reinforcing the CFRP on the flexural zone is effective to strengthening and restoring the initial capacity of the beam. The similar results of the experimental and numerical results confirmed their identified parameters of their models. They have mentioned that increasing the size of web openings has increased the loss of maximum load and for all the cases the loss of maximum load was lower for the strengthened beams with CFRP.

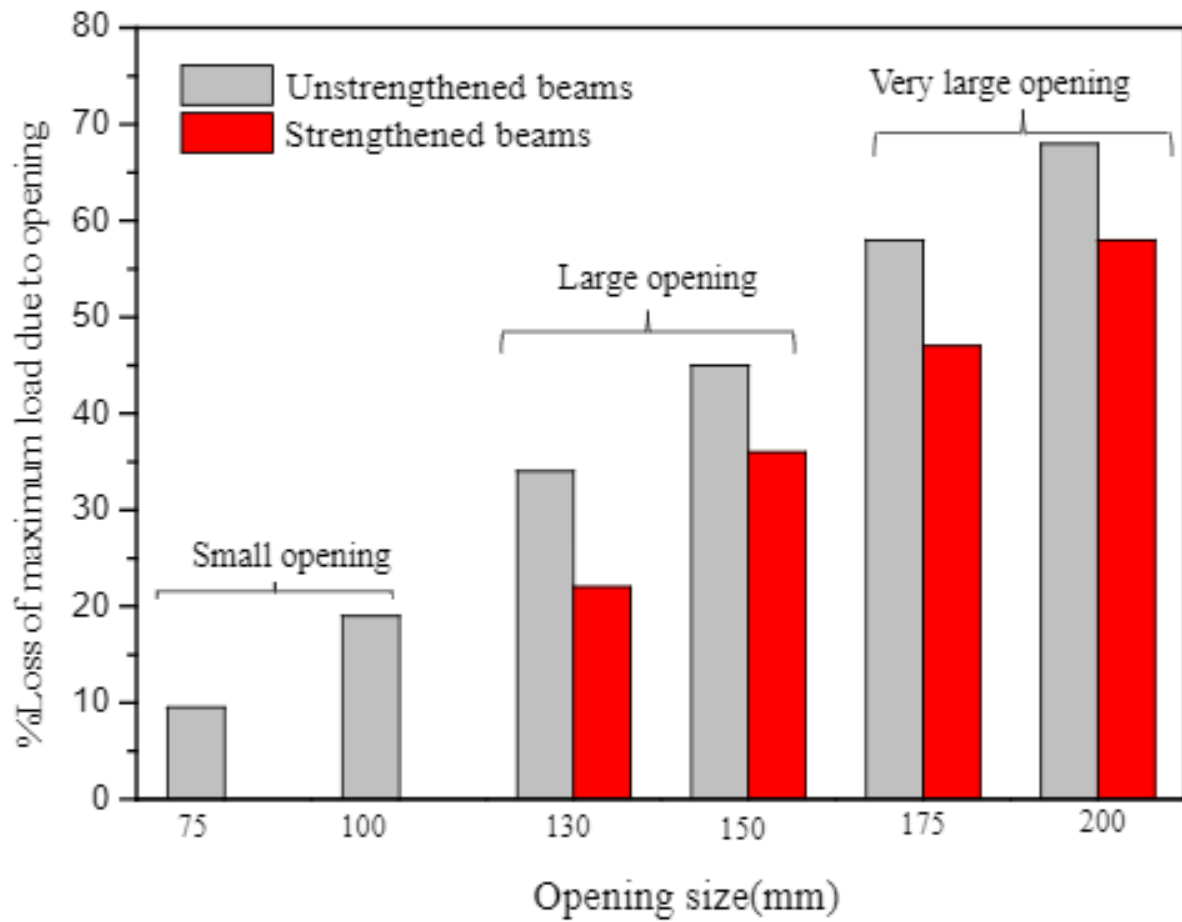


Figure 2.6. The impact of CFRP and web opening size on the properties beams with respect to maximum load [40].

Maysoun et al. [41] have investigated the influences of different strengthening shapes and methods with different sizes and various parameters. They employed CFRP layers with different length to strengthen the RCBs. Furthermore, they have investigated the flexural behavior of the beams with different conditions, experimentally and numerically.

As shown in Fig. 2.7, there is a good agreement between the experimental results and numerical simulations related to the load displacement curves of the sample. Moreover, the specimen B3 has the maximum load with about 16 ton attributed to the 2 layers with the length of 2 m CFRPs used for the strengthening of that.

Specimen's Name	Length of CFRP sheets used		Number of layers used (n)
	Positive B.M	Negative B.M.	
Ao	Control	Control	Control
A1	L = 50% $L_{total} = 1 \text{ m}$	L = 50% $L_{total} = 1 \text{ m}$	One layer
B1	L = 50% $L_{total} = 1 \text{ m}$	L = 50% $L_{total} = 1 \text{ m}$	Two layers
A2	L = 75% $L_{total} = 1.5 \text{ m}$	L = 75% $L_{total} = 1.5 \text{ m}$	One layer
B2	L = 75% $L_{total} = 1.5 \text{ m}$	L = 75% $L_{total} = 1.5 \text{ m}$	Two layers
A3	L = 100% $L_{total} = 2 \text{ m}$	L = 100% $L_{total} = 2 \text{ m}$	One layer
B3	L = 100% $L_{total} = 2 \text{ m}$	L = 100% $L_{total} = 2 \text{ m}$	Two layers

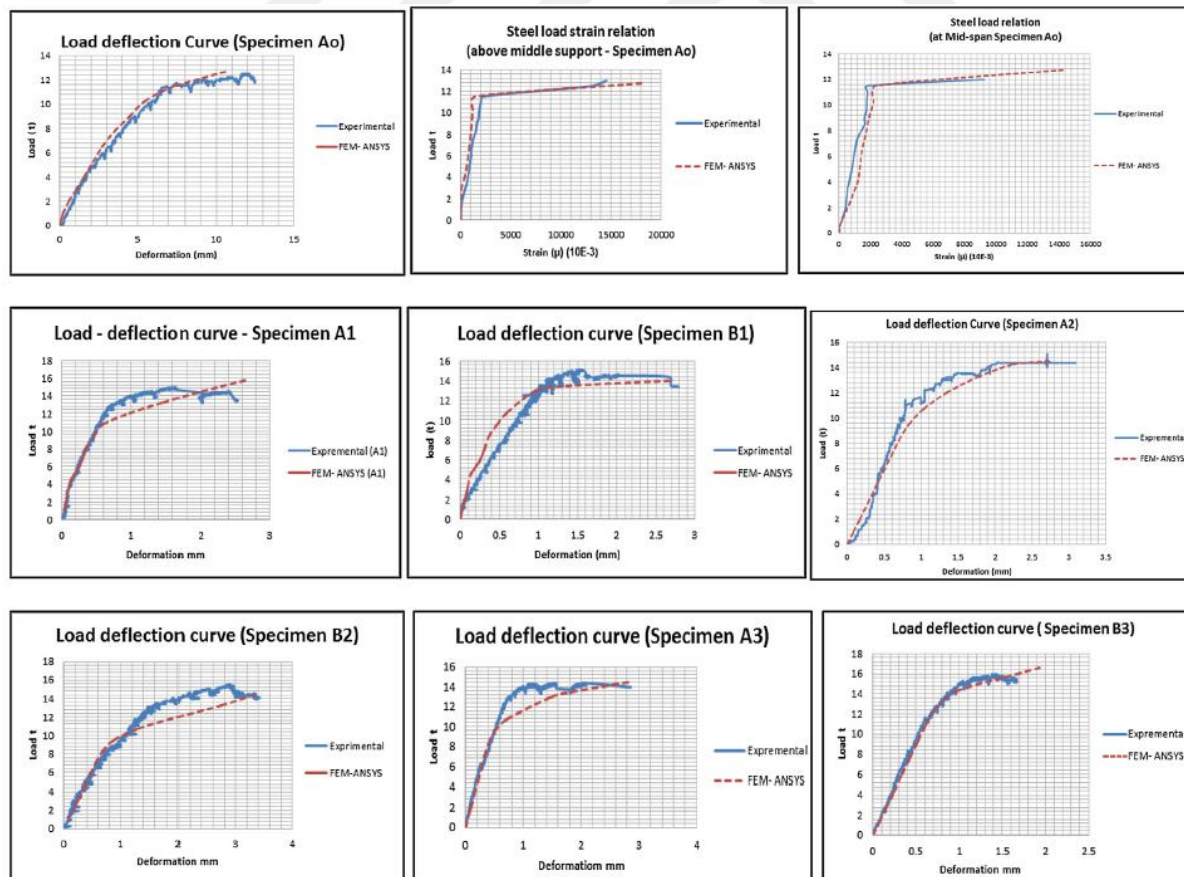


Figure 2.7. Deflection versus load curves of the beams strengthened with CFRP.

Seven beams were constructed experimentally and studied to discuss two parameters which are the length and number of layers of CFRP sheets.

Also, finite element Models (FEM) was developed by using ANSYS.

The experimental results were used as verification for the FEMs' results.

Test results showed that the common mode of failure in hogging zone is a rupture, while de-bonding occurs at the sagging zone.

When the number of layers has increased the mode of failure is likely de-bonding.

Despite many studies have been done investigating the structural behavior of the reinforced concrete beams with FRPs, there is a lack of information about the numerical analysis of the RCBs strengthened by FRPs under the cyclic loading. Furthermore, displacement control cyclic loading needs to be investigated more in detail. Moreover, effect of adding web opening with different size is very critical due to the increasing the application of these beams in the structures, therefore, in the current study, the effect of adding the web openings was investigated using numerical method.

3. NUMERICAL SIMULATION

In the current study, numerical method is utilized to perform the simulation using ABAQUS software that is a well-known and user friend analysis software package which is capable of solving a wide-ranging linear and non-linear problems. Mechanical properties such as density, inelastic and Hashin damage criteria of concrete as well as the mechanical properties of steel and CFRP and BFRP were defined to model by performing concrete damage plasticity (CDP) model. Isotropic damaged elasticity theory was considered for both compressive and tensile plasticity according to literature [42]. The parameters related to the CDP FE model have been listed in Table 3.1.

Uniaxial tensile and compressive mechanical performances of concrete are needed to characterize the CDP in ABAQUS. The relations for the stress-strain of uniaxial compression test and tensile test are as follows:

$$\sigma_c = E_0 (1 - d_c)(\varepsilon_c - \varepsilon_c^{pl}) \quad (1)$$

$$\sigma_t = E_0 (1 - d_t)(\varepsilon_t - \varepsilon_t^{pl}) \quad (2)$$

Where σ_c , d_c , E_0 , is the compressive stress, compressive damage variable and initial elastic modulus of the material, respectively. Also, σ_t , d_t , E_0 , is the tensile stress, tensile damage variable, respectively. Furthermore, ε_c and ε_c^{pl} are compressive strain and compressive plastic strain, respectively. Also, ε_t and ε_t^{pl} are the strain under the tension and tensile plastic strain, respectively.

Table 3.1. CDP parameters of Concrete [43].

Dilation Angle (Ψ)	Eccentricity (ϵ)	f_{b0}/f_{c0}	K	Viscosity (μ)
56	0.1	1.16	0.667	0.0001

The tensile and compression behavior of concrete were defined and utilized for both conditions of prior to ultimate strength and post peak stress.

A developed model by Lubliner et al. [44] has been used in ABAQUS for failure of the concrete. This model has been modified by several researchers [43]. The model offered by Lee et al. was chosen for this study. The plasticity properties may be explained by many phenomena, like strain softening, deterioration of the material gradually, and volumetric expansion, and consequently a decrease in strength and stiffness of the concrete. More details about the CDP model and the related theories is available in the ABAQUS Analysis User's Manual [45]. The plastic properties for stress and strain for damage of the concrete can be achieved by the Equations (3) and (4) to measure damage throughout the degradation only in the softening stage where stiffness is proportional to the cohesion of the sample.

$$\frac{E}{E_0} = \frac{C}{C_{max}} = (1 - d) \quad (3)$$

$$\varepsilon^{-p} = \varepsilon^p - \frac{d}{1-d} \frac{\sigma}{E_0} \text{ and } \varepsilon^{-p} = \varepsilon - \frac{f}{E_0} \quad (4)$$

Where C is cohesion in the criteria of the yield strength, that is also proportional to stress, C_{max} is equal to the strength of the concrete, d and f are damage factor and the tensile or compressive strength of concrete.

Furthermore, damage compression for model elements and tensile factors is evaluated via Equations (5) and (6), separately.

$$d_c = 1 - \frac{\sigma_c E_c^{-1}}{\varepsilon_c^{pl} \left(\frac{1}{bc} - 1 \right) + \sigma_c E_c^{-1}} \quad (5)$$

$$d_t = 1 - \frac{\sigma_t E_c^{-1}}{\varepsilon_t^{pl} \left(\frac{1}{bt} - 1 \right) + \sigma_t E_c^{-1}} \quad (6)$$

Where σ_c is the compressive stress and σ_t is tensile stress. E_c is the concrete modulus elasticity, ε_t^{pl} is the plastic. The values of bc and bt are recommended by [46] and equal to 0.7 and 0.1, respectively.

There are many kinds of tests to determine the flexural strength of a material such as three-point bending and four-point bending tests. In the current work four-point bending and also three-point bending tests were simulated in ABAQUS and the schematic of four-point bending test and

detailed model used in the simulations is illustrated in Figure 3.1. Beams with the width, height and length of 300 mm, 200mm, and 2400 mm, respectively were used as a base model to observe the effect of adding web opening and CFRP on the flexural strength of the beam.

Also, the beam was reinforced via 4 bars with the diameters of 8 mm and c/c of 152 mm and series of stirrups with an interval distancing of 100 mm c/c (see Fig. 3.1). The young modulus of steel bars and stirrups was defined as 200 GPa and the mechanical properties of the steel were set in the ABAQUS software. The compressive strength (f_c) of the concrete used in the study was 30 MPa.

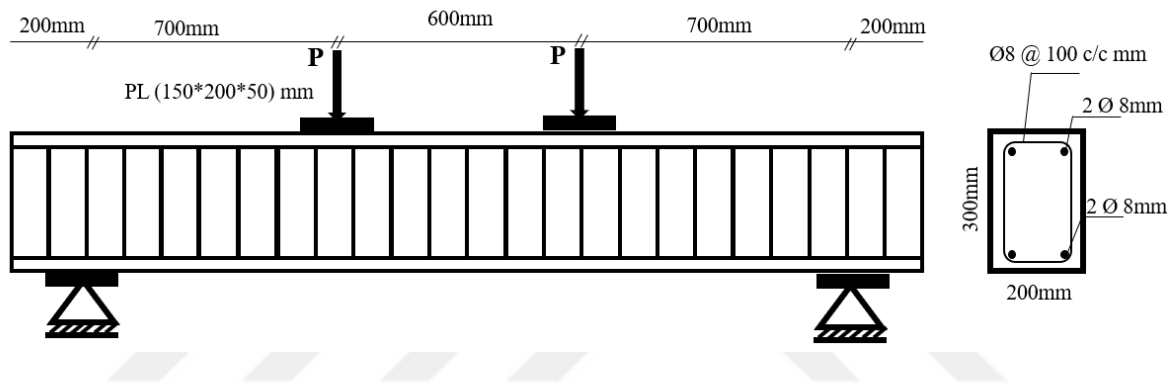


Figure 3.1. Schematic design of four-point bending test and detailed model of the reinforced beam used in the simulations.

In following section, a brief explanation of the modelling for beam and FRPs used in the current work has been written. The Dynamic behavior of concrete used for the simulation and also damage properties used in ABAQUS for the simulation is presented in Table 3.2.

Table 3.2. Dynamic behavior and tensile damage values of concrete used in the simulation.

TENSILE (CDP)		TENSILE DAMAGE		
stress	in-strain	stress	damage	in-strain
3450652.112	0	3450652	0	0
2295713.038	0.00029	2295713	0.740058	0.00029
1884035.156	0.000549	1884035	0.868129	0.000549
1651583.006	0.000802	1651583	0.916419	0.000802
1496056.714	0.001052	1496057	0.940729	0.001052
1382096.603	0.0013	1382097	0.955019	0.0013

3.1 MECHANICAL MODELING

Firstly, the beam, steel embedded region inside of the concrete beam, FRP layers, and rigid bodies for support and applying the deformation were designed in the part module of the ABAQUS software. After that, the material properties of the steel, BFRP and CFRP, and concrete were defined in the property module. Subsequently, the four-point bending setup was assembled in assembly module of the software as shown in Fig. 3.2.

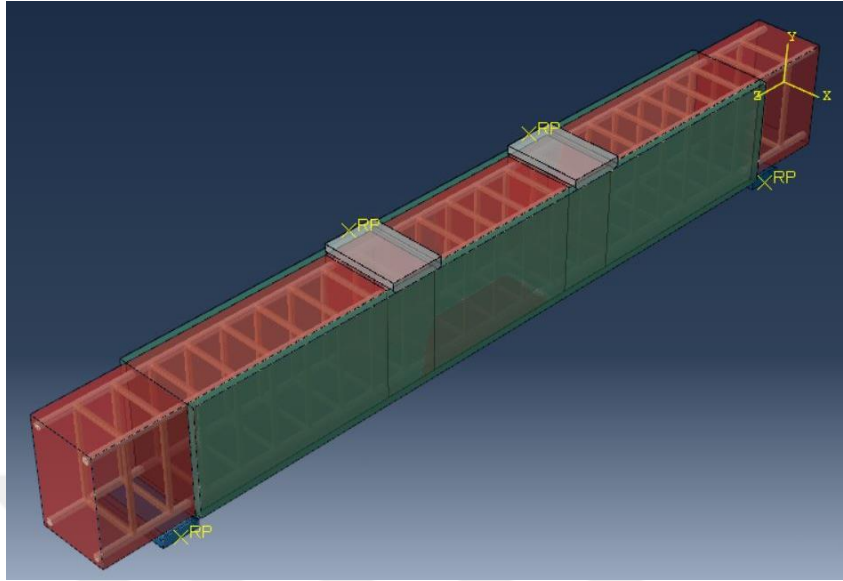


Figure 3.2. Assembly of the four- point bending system simulated in this work.

Also , Fig. 3.3 demonstrates the setup consist of 23 stirrups and 4 steel bars inside of the beam to make the reinforced concrete beam. Furthermore, four rectangular rigid bodies were designed to make the supports at both side of the beam and two for applying the load from the top of the system which can be seen in Fig. 3.2.

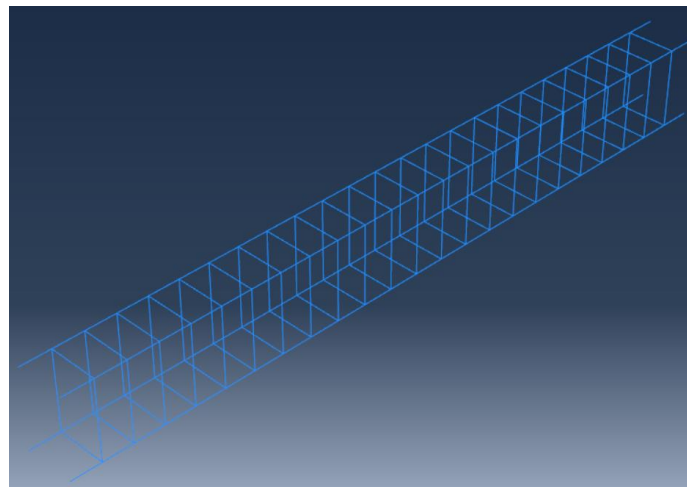


Figure 3.3. Embedded stirrups and bars of steel.

Consequently, U shape wrapped polymer were design to see the effect of different FRPs such as BFRP and CFRP on the flexural strength of the reinforced concrete beams. The design of this laminated layer can be seen in Fig. 3.4.

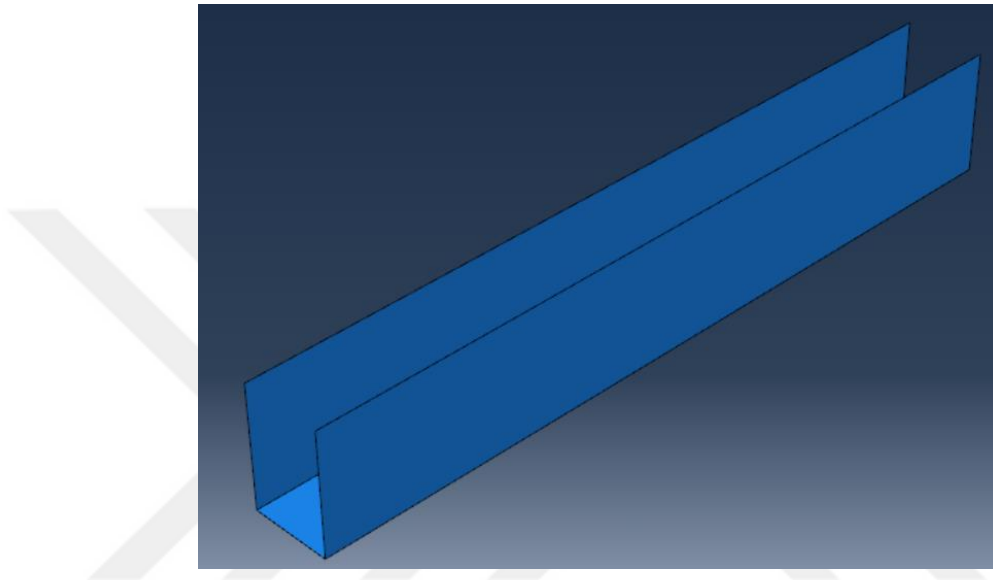


Figure 3.4. The design of the U shape wrapped FRP.

For the next part of the modelling in ABAQUS, the interactions between different parts of the system and constraints and contacts were defined. Afterward, in mesh module all the parts were meshed one by one to discretize the parts for numerical solution. Although, low element size may give better results, the low element size increases the number of the elements which subsequently increase the simulation time. Therefore, we have tried to optimize the number of the elements and element size to achieve a reliable result and compute the problem faster. In most of the cases of this thesis, the approximate global size was defined as 0.05. Fig 3.5 demonstrates the system for the four-point bending test after mesh. Also, the meshed FRP laminates were shown in Fig. 3.6.

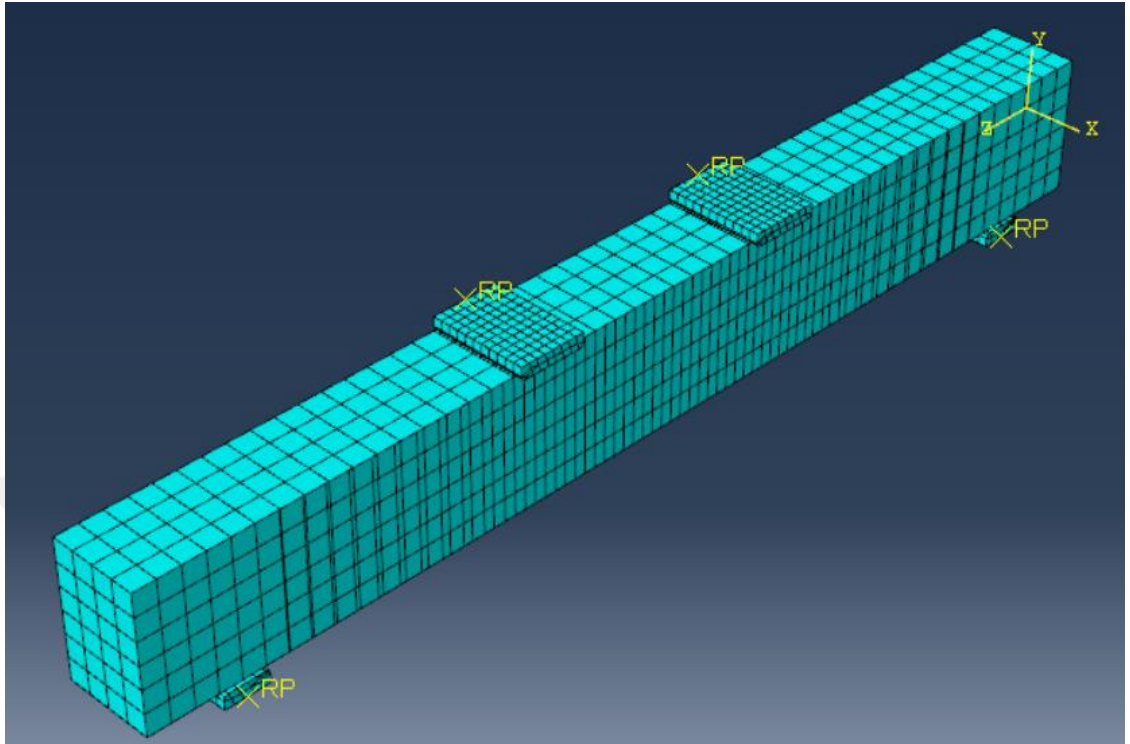


Figure 3.5. Meshed setup.

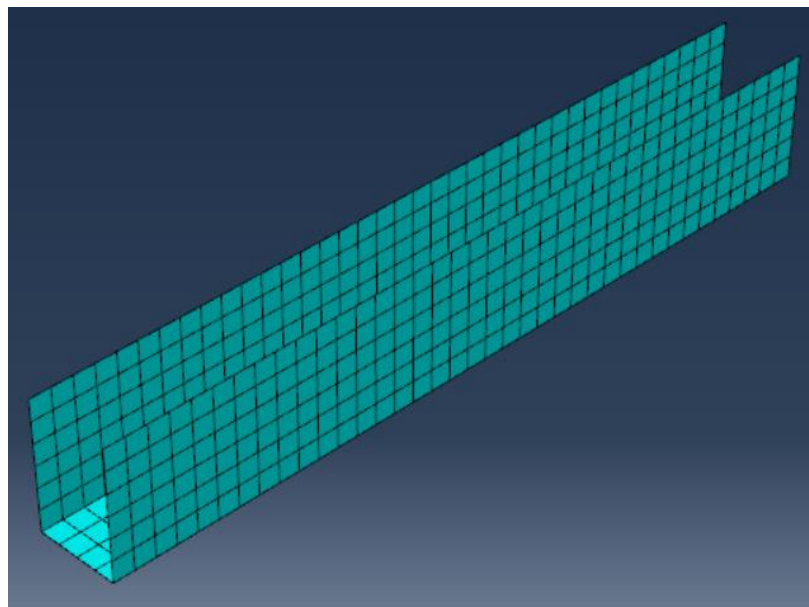


Figure 3.6. Meshed FRP laminates.

In Abacus software, three types of cracks can be modeled to consider material failure, which should be defined in the material properties section.

- a. Smeared Crack Concrete Model
- b. Brittle Crack Concrete Model
- c. Concrete Damage Plasticity Model

In the plastic failure model, the software considers two main assumptions in the rupture mechanism; Tensile cracking and crushing, and in the standard model and in the explicit model, both allow the modeling of damage and gradual failure in the adhesive layers, which is defined in terms of separation tension. In explicit type analysis, it is possible to model damage and gradual degradation for adhesive elements with conventional materials. Separation tensile reaction damage is defined in the same general context as for conventional materials. This general framework allows the combination of multiple damage mechanisms that act simultaneously on a material. Each destruction mechanism consists of 3 parts: the initial damage criterion, the law of increasing damage (damage growth) and the separation (removal) of elements in case of complete damage. While this general framework for separation tensile reactions and conventional materials is similar, many details differ in how different materials are defined. Details of damage modeling in the separation tensile reaction are provided below. The initial reaction of the adhesive element is linear as described above. However, when the initial damage criterion is observed, the material damage occurs in accordance with the law of damage evolution (damage) defined for the user. Fig. 3.7 shows an example of a separation tensile reaction with a failure mechanism. If the initial damage criterion is determined without considering the associated damage evolution model, the software evaluates the initial damage criterion for output purposes only and will have no effect on the adhesive reaction (in other words, no damage occurs) [47].



Figure 3.7. Traction-separation curve [47].

4. FLEXURAL BEHAVIOR UNDER THE FOUR-POINT BENDING

The results of the simulations were classified for two different cases of reinforced with and without CFRP laminates. U shape wrapped CFRP have been employed to observe the effect of CFRP on the flexural behavior of the beams under the cyclic loading. Furthermore, rectangular web openings with different sizes at the center of the beam have been investigated.

4.1 FLEXURAL BEHAVIOR OF REINFORCED CONCRETE BEAM UNDER THE CYCLIC LOADING

An increasing cyclic loading were applied on the beams with the specific time intervals until the failure of the beam. The main concrete part was considered as the important part for the failure. The loading curve is illustrated in Fig. 4.1 Displacement for each cycle were chosen as 1.5 mm. Three rectangular web opening were used with different side sizes of 40%, 50%, and 60% of the depth in order to see the effect of web opening size on the flexural behavior of the beam for both cases of with and without CFRP. U shape wrapped CFRP were tie to the beam prior to simulation. The side sizes of the rectangular web openings were 12, 15, and 18 mm ,respectively.

The boundary conditions were selected for both rigid bodies at sides of the beams as an ENCASTRE ($U_1=0$, $U_2=0$, $U_3=0$, $UR_1=0$, $UR_2=0$, $UR_3=0$) and friction were defined between the beam and rigid bodies in order to give the ability of moving in 2 directions to the beam on the supports. Loading was applied using a displacement control loading via rigid body at the top of the beam and unload to the initial point and repeating this process.

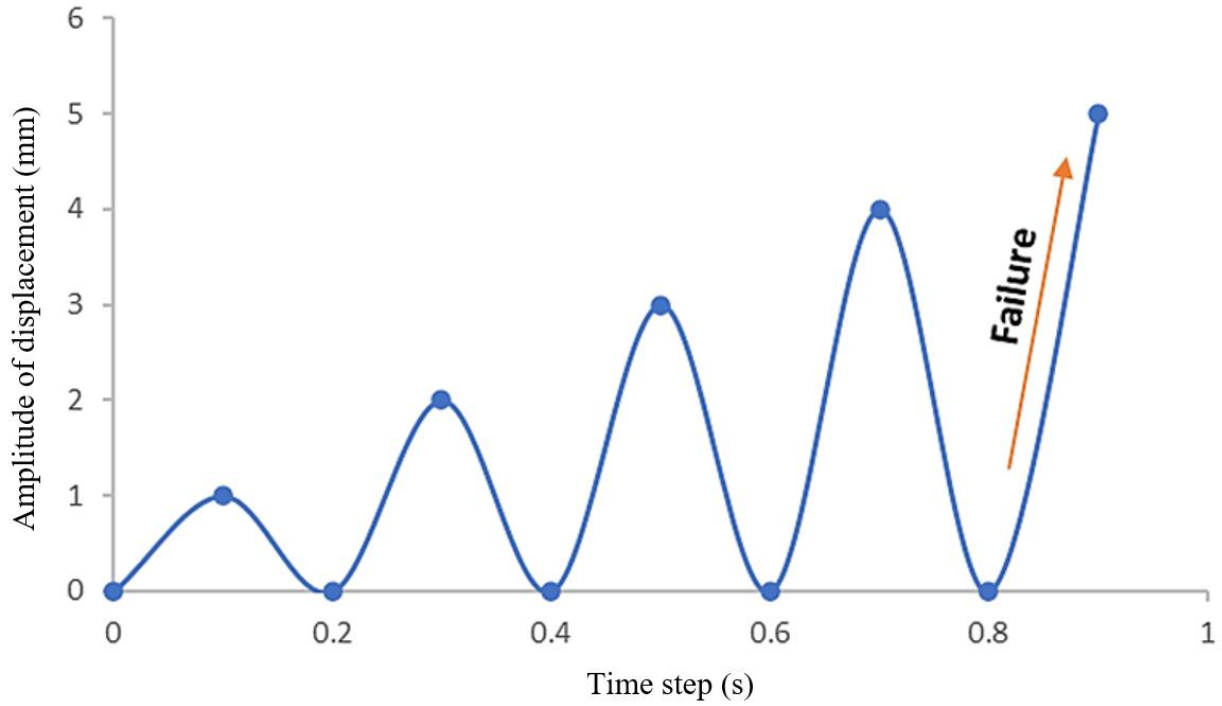


Figure 4.1. Amplitude of cyclic loading in different time steps of simulation.

Fig. 4.2 demonstrates the effect of adding web opening on the flexural behavior of the RC beams with respect to the number of cyclic loading. It can be observed that with increasing the size of the web opening from 40% of the width of the beam to 60%, the maximum von mises stress of the beam has reached to the maximum compressive strength of the beam at lower number of the cycles.

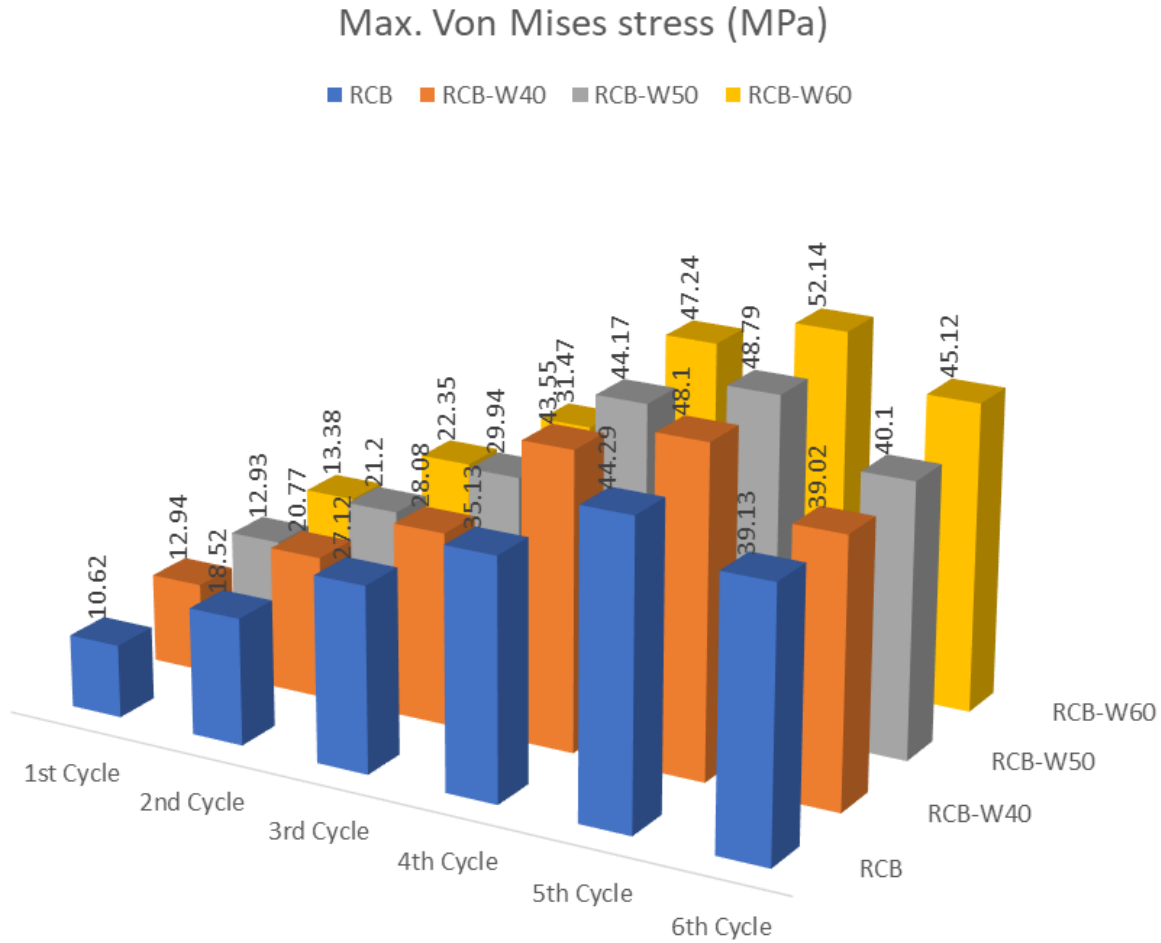


Figure 4.2. Maximum Von Mises stress of the beams with and without web opening at different cycles.

Fig. 4.3 shows the start of the yielding on the concrete beam and increasing the number of the yielded elements throughout that in further cycles with increasing the displacement amplitude. The results of the simulation of the beam were in a good agreement with the literature in case of start of the yielding form the bottom part of the beams and propagating through the sample. Then with increasing the stress level at further cycles the top parts of the beam was also yield from the compressive stress.

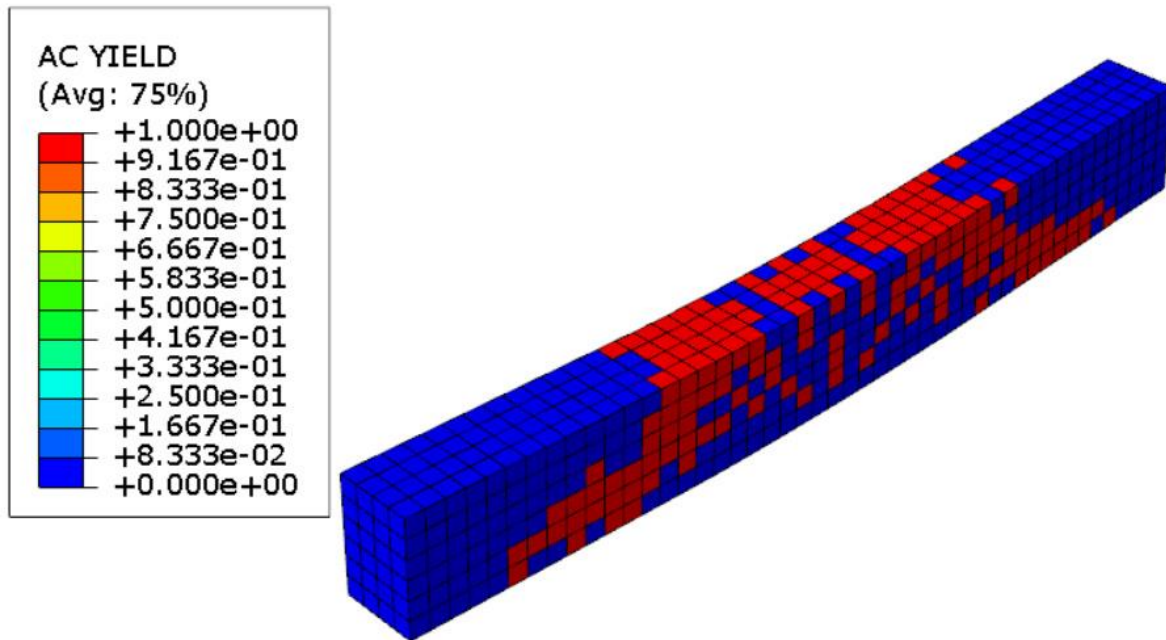


Figure 4.3. Yielding criteria on the RCB during the cyclic loading.

The maximum von Mises stress distribution on the reinforced concrete beam after the fifth cycle was shown in Fig. 4.4. It can be seen that the von Mises stress value has reached to about 43 MPa at the position of the contact between the supports and beam at the both sides of the bottom of the beam.

The equivalent plastic strain on the concrete beam can be seen in Fig. 4.5. In the figure it can be observed that the maximum PEEQ is at the compressive zone at the top of the beam where the beam is contact with two rigid plates. With applying the displacement from the rigid bodies to the beam the compressive stress generates above the neutral line of the beam then the maximum plastic strain occurs on the zones that displacement directly applied.

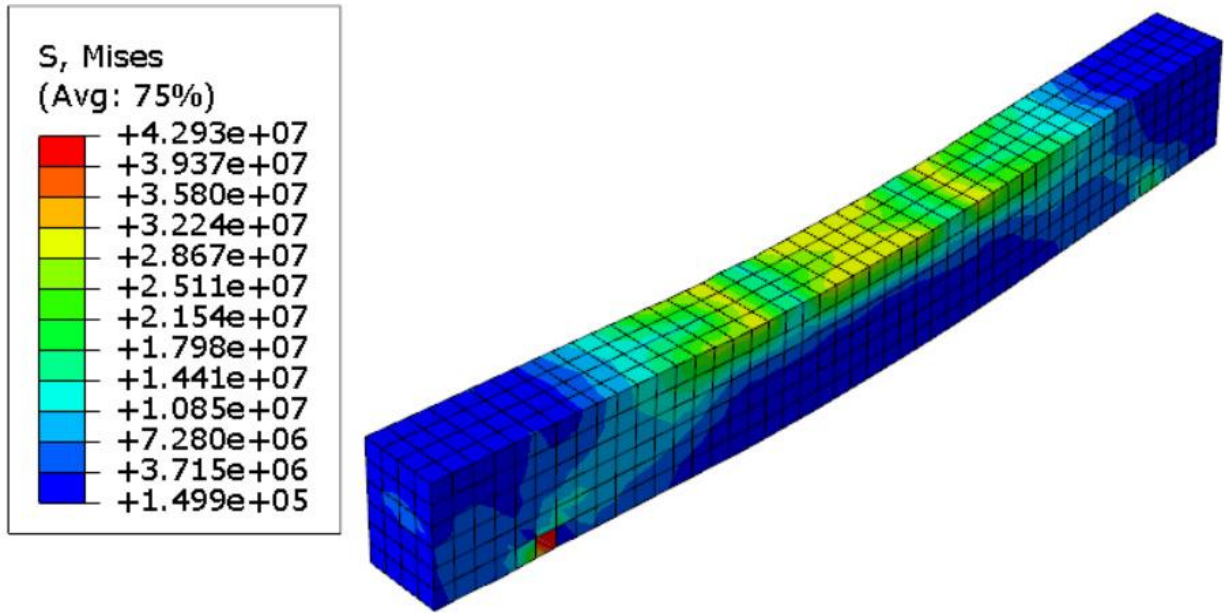


Figure 4.4. The maximum von Mises stress distribution on the reinforced concrete beam after the fifth cycle.

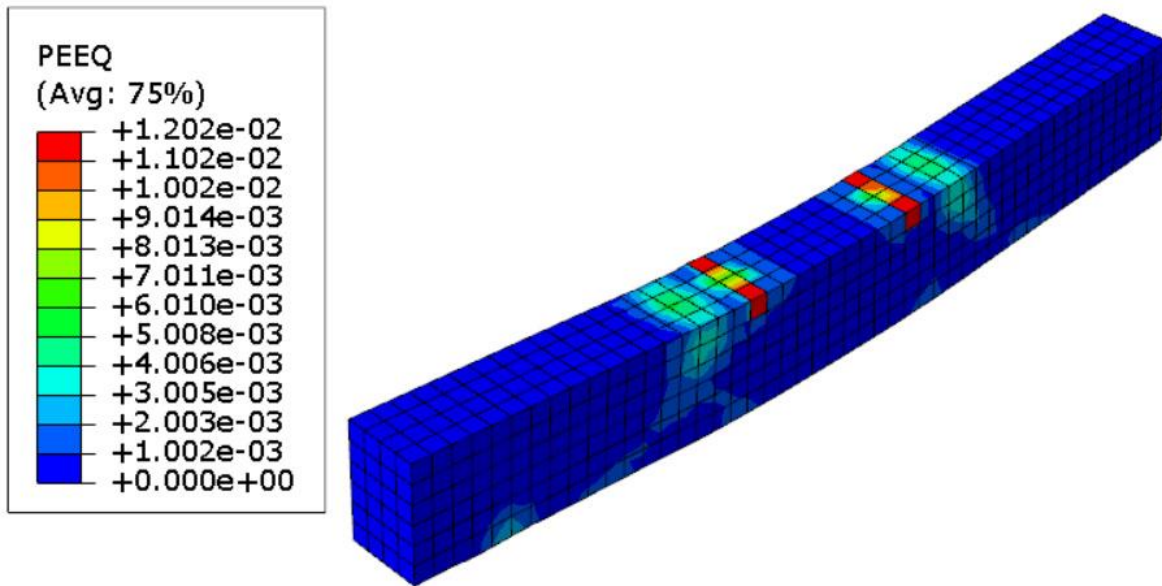


Figure 4.5. The equivalent plastic strain distribution on the reinforced concrete beam after the fifth cycle.

Also, the von Mises stress distribution on the steel bars and stirrups is demonstrated in Fig. 4.6. As shown in Fig. 4.6, the most critical zone on the embedded region was the bottom bars where the maximum stress was 382.5 MPa and that was higher than the yield strength of the steel used in this model.

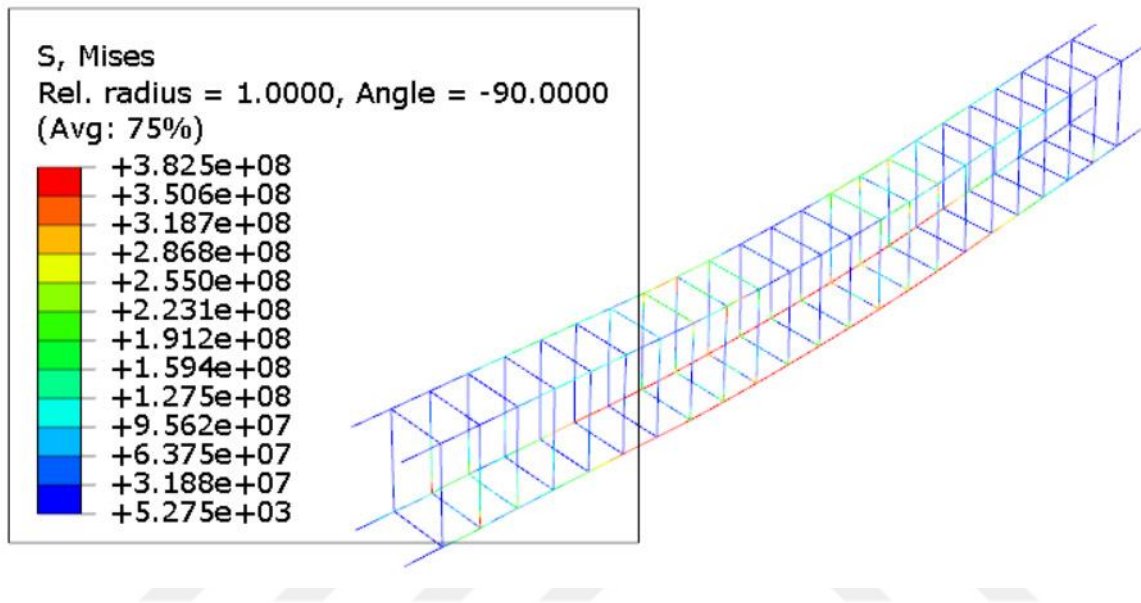


Figure 4.6. The maximum von Mises stress distribution on the reinforced concrete beam.

The effect of adding web opening on the stress distribution on the beam also has been observed for the case with CFRP. With the addition of web opening with different ratios of 40%, 50%, and 60%, it can be observed that the level of maximum von Mises stress after each cycle of loading was enhanced due to the stress concentration on the corners of the rectangular web openings and top of the opening.

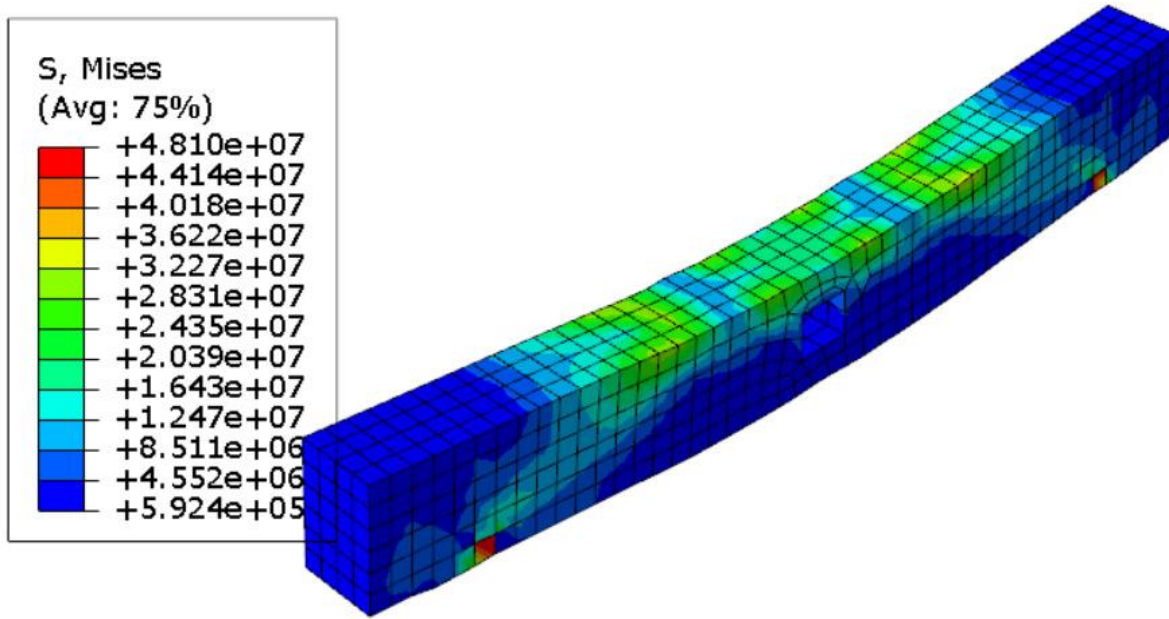


Figure 4.7. The maximum von Mises stress distribution on the RCB-W40 after the fifth cycle.

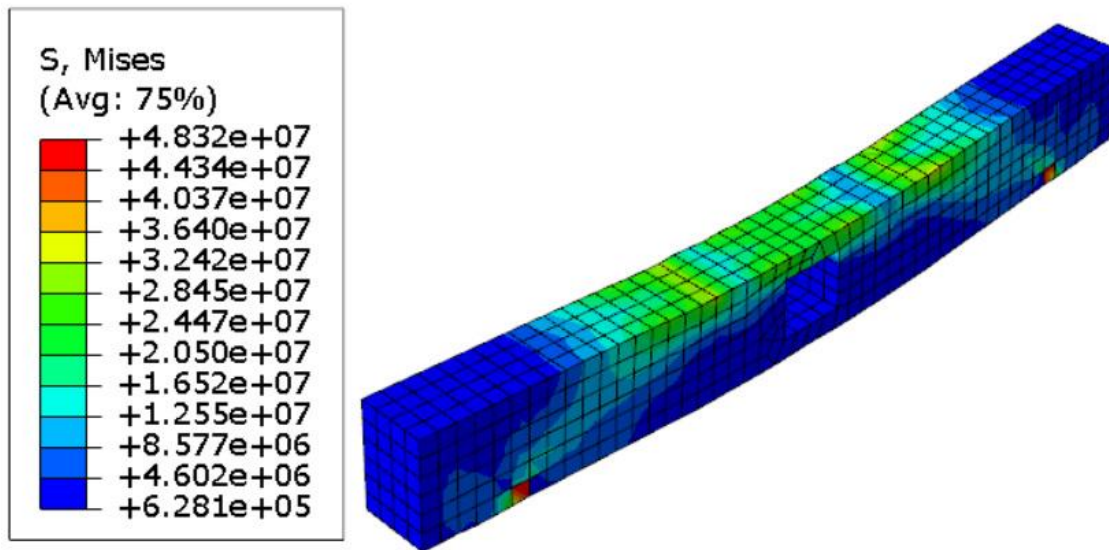


Figure 4.8. The maximum von Mises stress distribution on the RCB-W60 after the fifth cycle.

Regarding the results of the Fig. 4.2, it can be observed that the level of maximum von Mises stress for RCB-W60 is lower than the others approximately at all the cycles. But this is related to

the localization of deformation in this case and this case cannot be applicable for the beams. Fig. 4.9 shows the results of equivalent plastic strain and deformation at the 5th cycle for RCB-W60, respectively. As it shown in Fig. 4.10, it can be seen that the steel bars and stirrups have been yield and reach to the stress level of 403 MPa which was higher than that of the beam without web opening. This can be attributed to the stress concentration of the beam at the center after adding the web opening.

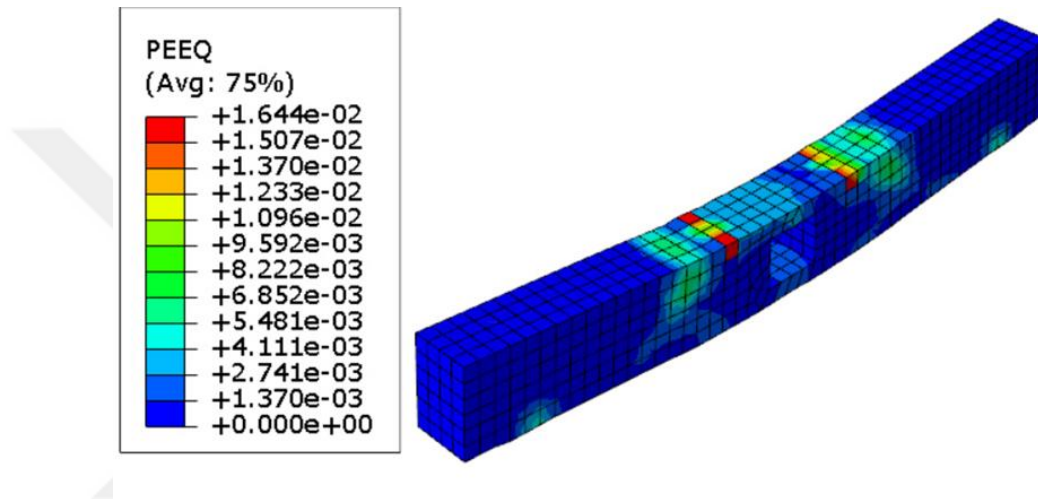


Figure 4.9. The equivalent plastic strain distribution on the RCB-W60 after the fifth cycle.

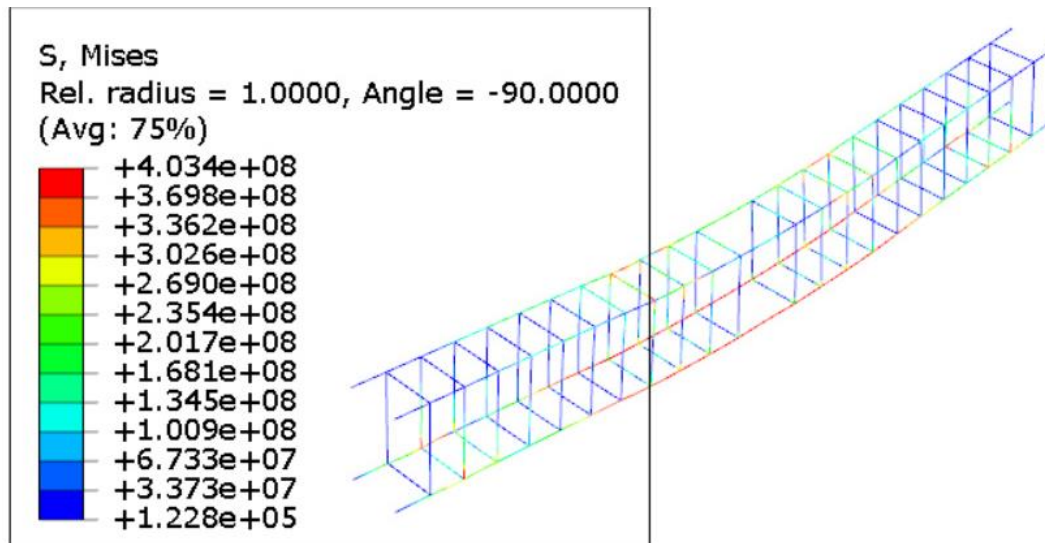


Figure 4.10. The maximum von Mises stress distribution on the embedded region on the RCB-W60.

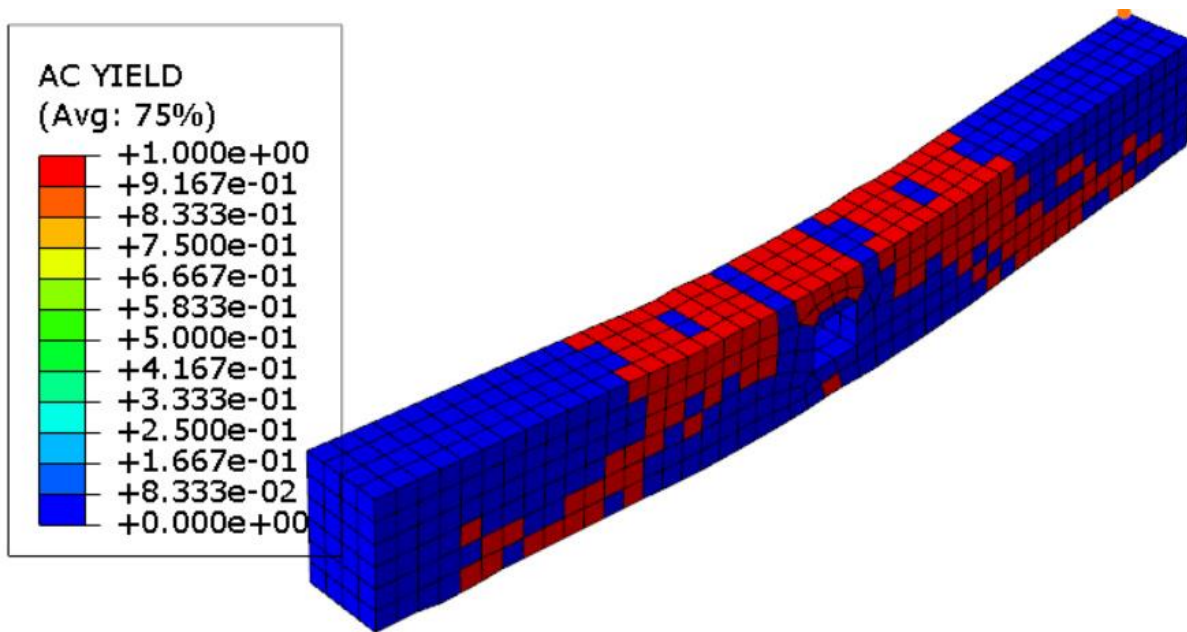


Figure 4.11. Yielding criteria on the RCB-W40.

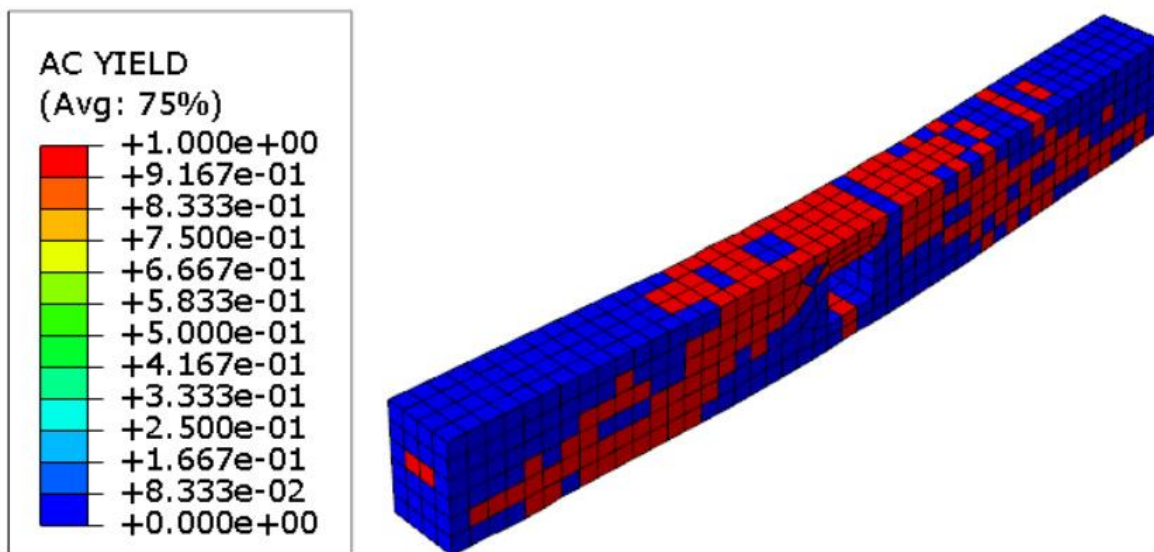


Figure 4.12. Yielding criteria on the RCB-W50.

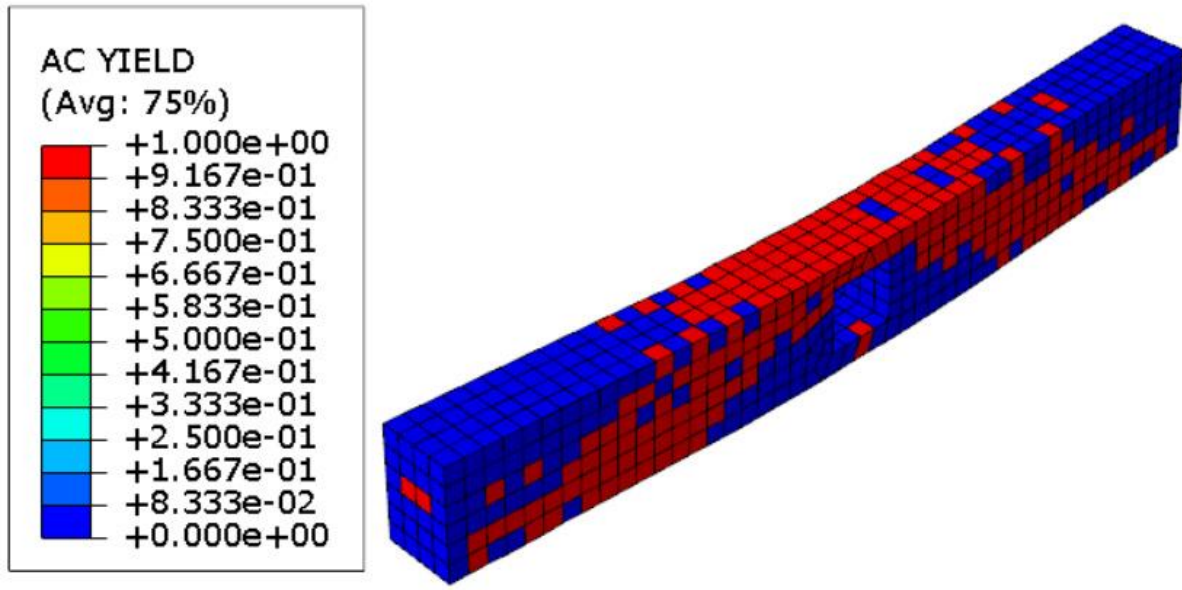


Figure 4.13. Yielding criteria on the RCB-W60.

4.2 FLEXURAL BEHAVIOR OF CFRP REINFORCED CONCRETE BEAM UNDER THE CYCLIC LOADING

CFRP was used to enhance the flexural strength of the system. Firstly, U shape CFRP attached to the reinforced concrete beam to investigate the effect of the reinforcement method. The mechanical properties of the CFRP defined to the ABAQUS are listed in Table 4.1.

Table 4.1. Mechanical properties of CFRP.

E_1 (N/mm ²)	E_2 (N/mm ²)	ν_{12}	G_{12} (N/mm ²)	G_{13} (N/mm ²)	G_{23} (N/mm ²)
23000	17860	0.3	10000	10000	10000
Longitudinal Tensile Strength (N/mm ²)	Longitudinal Compressive Strength (N/mm ²)	Transverse Tensile Strength (N/mm ²)	Transverse Tensile Strength (N/mm ²)	Longitudinal Shear Strength (N/mm ²)	Transverse Shear Strength (N/mm ²)
3450	2760	133	536	117	117

The results of the flexural loading simulation of the beam reinforced by U shape wrapped CFRP laminate is demonstrated in Fig. 4.14. With comparing the results of the simulations with U shape wrapped CFRP and without CFRP, it can be observed that for all the cases attachment of the CFRP has decreased the von Mises stress levels of each cycle. Also, considering the web openings with different sizes, it was asserted that the web opening caused to the failure faster than that of the case without the opening.

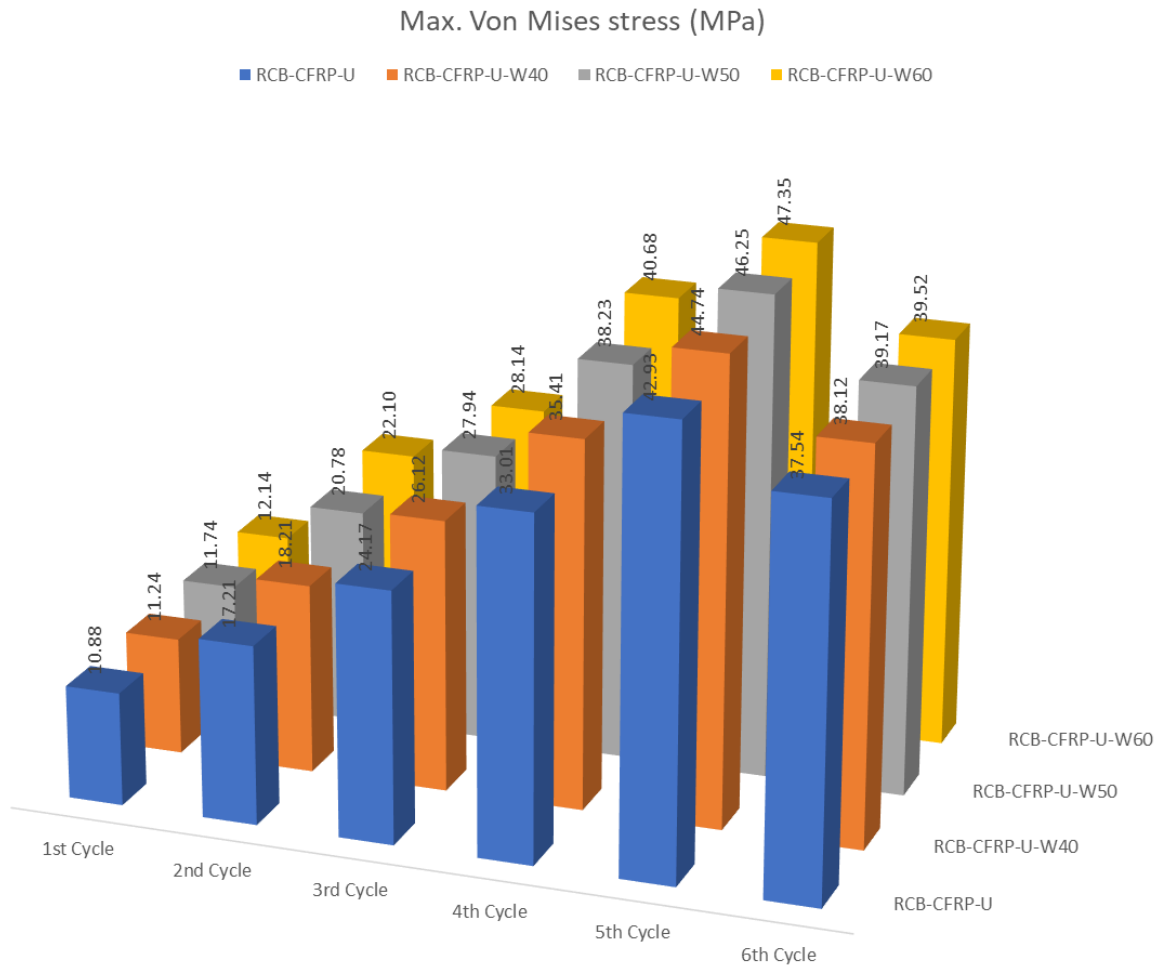


Figure 4.14. Maximum Von Mises stress of the RCB-U-CFRP with and without web opening at different cycles.

Fig. 4.15 demonstrates the yielding on the RCB U shape wrapped CFRP and the same behavior of RCB without FRP reinforcement. With increasing the stress level at further cycles the top parts of the beam was also yield from the compressive stress.

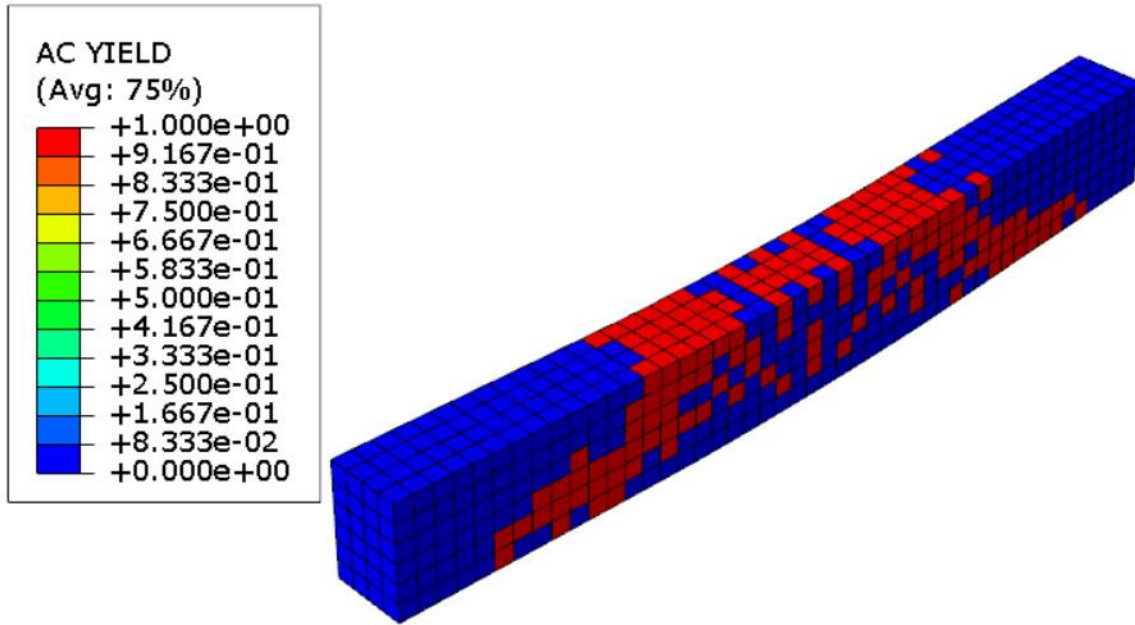


Figure 4.15. Localization of deformation on the top of the web opening part and failure of the RCB-CFRP-U sample.

The maximum von Mises stress distribution on the reinforced concrete beam after the fifth cycle was shown in Fig. 4.16. It can be seen that the von Mises stress value has reached to about 43 MPa at the position of the contact between the supports and beam at both sides of the bottom of the beam. Furthermore, at the top part of the beam at both sides of the loading rigid bodies where the beam is under the compressive load higher than 30MPa which is the ultimate compressive strength of the concrete.

Also, Fig. 4.17 demonstrates the deformation of the beam and setup after the sixth cycle. It can be seen that the maximum deflection occurs on the center of the beam between the two rigid bodies where the loads are applied.

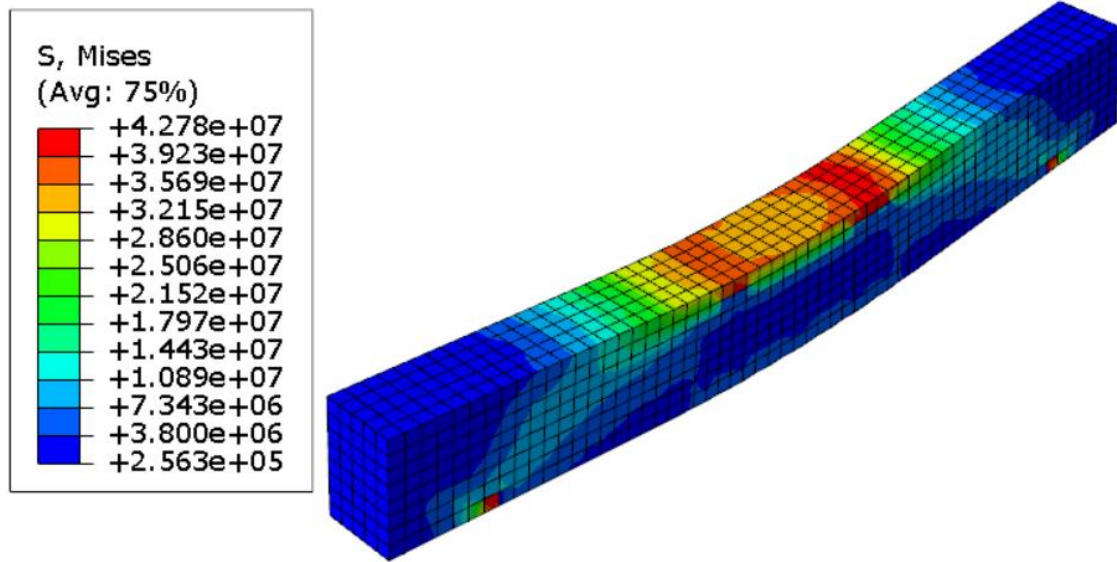


Figure 4.16. The maximum von Mises stress distribution on the RCB-U-CFRP after the fifth cycle.

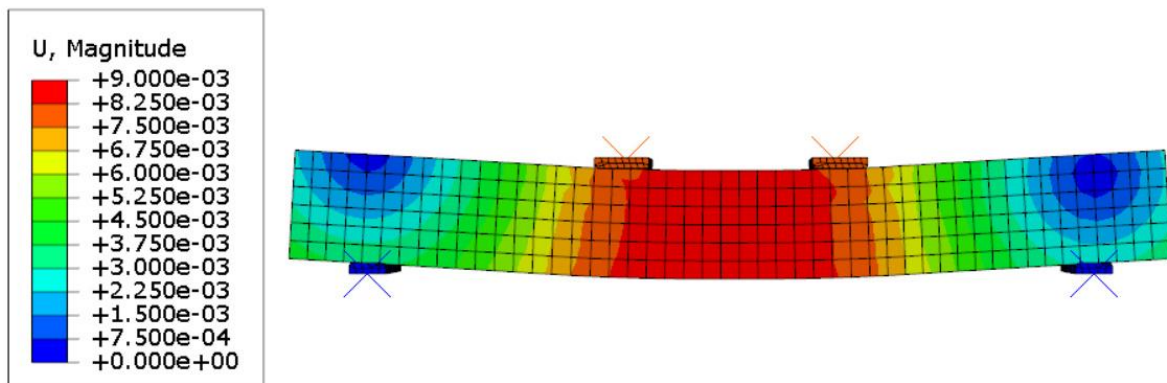


Figure 4.17. The deformation distribution on the setup after the sixth cycle.

Similarly, the von Mises stress distribution on the steel bars and stirrups is demonstrated in Fig. 4.18. As shown in Fig. 4.18, the most critical zone on the embedded region was the bottom bars where the maximum stress was 370.8 MPa and that was higher than the yield strength of the steel

used in this model. As indicated in the figure the top bars are under the compressive stress and the bottom bars are under the tension. Also, comparing the results of the stress distribution on the embedded region in RCB and RCB reinforced with CFRP, it can be asserted that the stress applied on the bars and stirrups for the case with CFRP was lower than the RCB without CFRP reinforcement due to the supportive role of the CFRP.

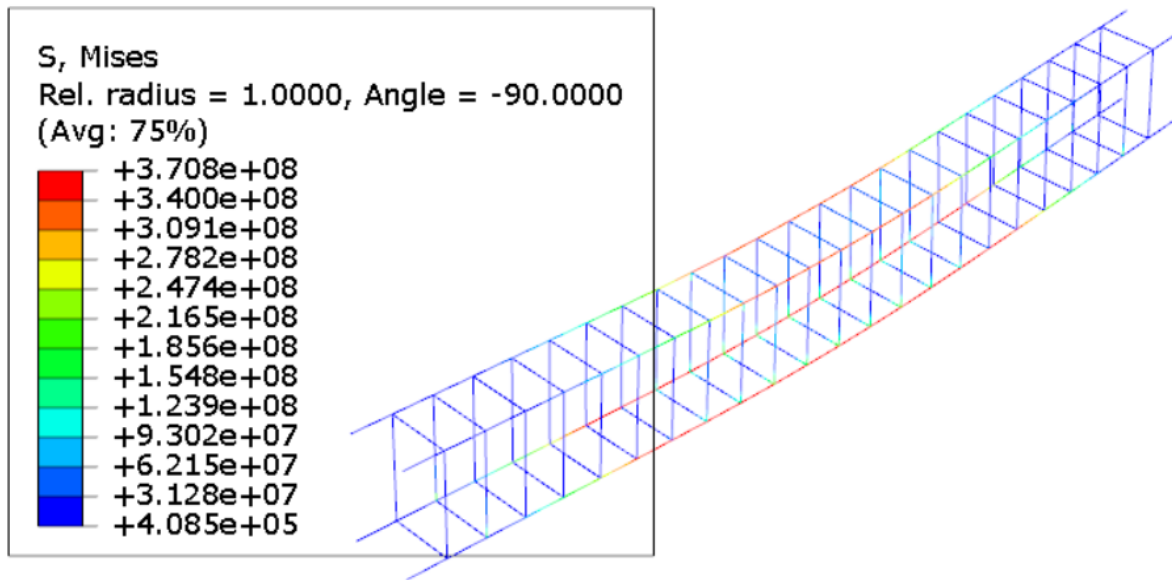


Figure 4.18. The maximum von Mises stress distribution on the embedded region of RCB-U CFRP.

With the addition of web opening with different ratios of 40%, 50%, and 60%, it can be seen that the level of maximum von Mises stress after each cycle of loading was enhanced due to the stress concentration on the corners of the rectangular web openings and top of the opening. Moreover, with increasing the size of web opening ratio the stress level enhanced and with comparing the results of the flexural simulation of RCB with and without CFRP, it can be asserted that the CFRP has reduced the level of stress at each cycle on the beam. Furthermore, it can be seen that stress levels have exceeded 40MPa after even fourth cycle with adding the web openings (see Fig. 4.19 and Fig. 4.20).

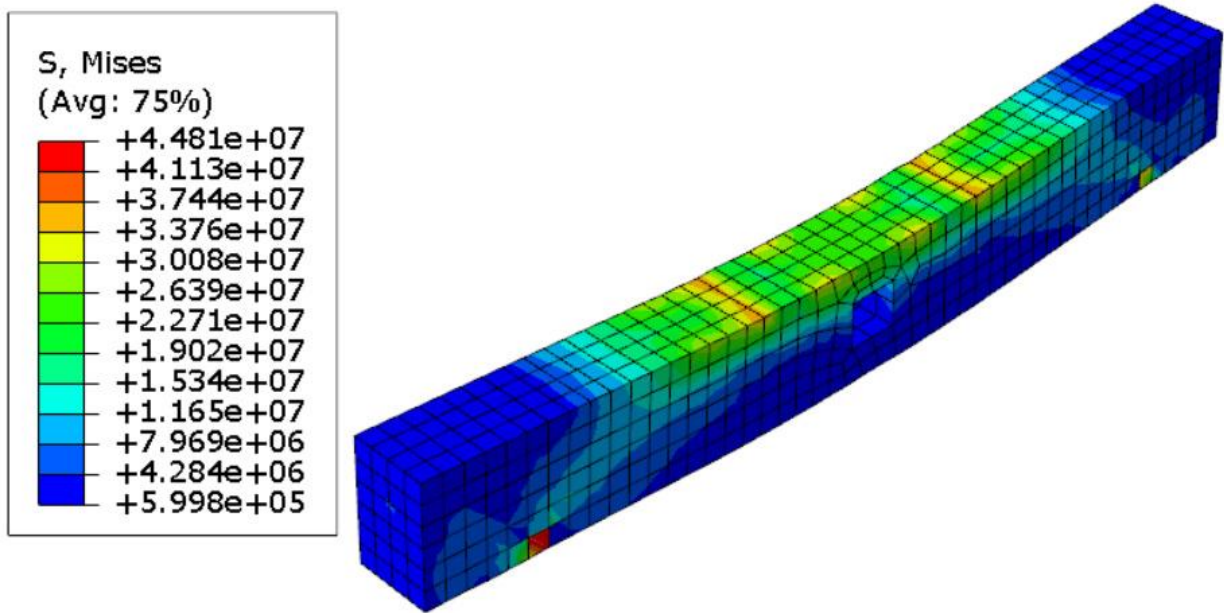


Figure 4.19. The maximum von Mises stress distribution on the RCB-CFRP-U-W40 after the fourth cycle.

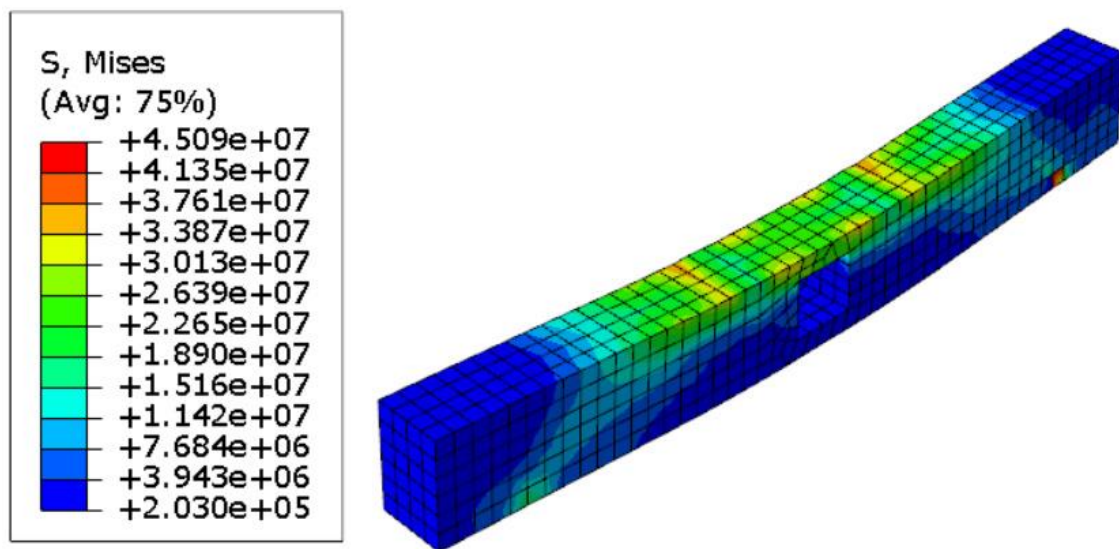


Figure 4.20. The maximum von Mises stress distribution on the RCB-CFRP-U-W60 after the fourth cycle.

Additionally, with observing the yielding criteria after applying the cyclic loading on the CFRP reinforced beams, it is clear that overall flexural behavior of the beams with CFRP reinforcements are better than the beams without CFRP. However, the same pattern was observed for the RCB-CFRPs with different web opening sizes (see Fig. 4.21, 4.22, and 4.23). With comparing the results of the simulation for the RCB without the CFRP laminates and with CFRP laminates, it can be understood that the attachment of the CFRP layers has prevented the propagation of yielding to the most parts of the beam and in the beams with web openings it is mostly concentrated around the rectangular web opening sides, top, and corners.

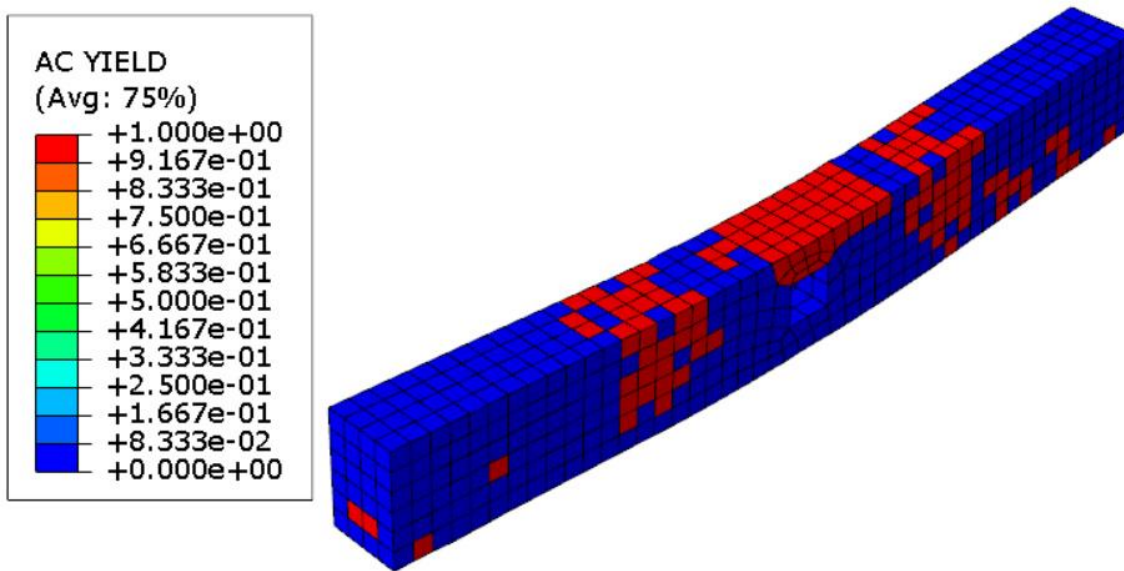


Figure 4.21. Yielding criteria on the RCB-CFRP-U-W40.

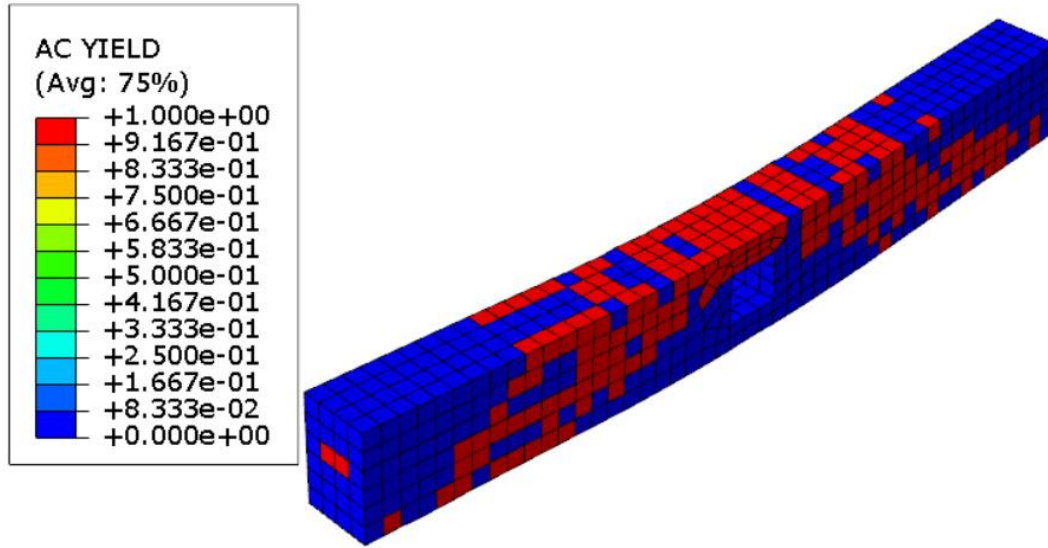


Figure 4.22. Yielding criteria on the RCB-CFRP-U-W50.

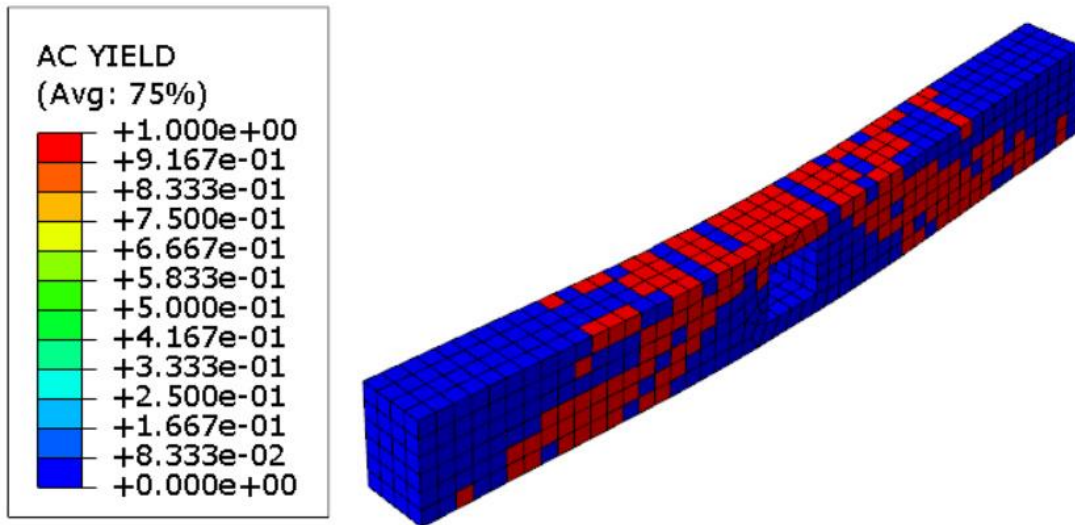


Figure 4.23. Yielding criteria on the RCB-CFRP-U-W60.

Also, the maximum von Mises stress distribution on the CFRP laminates is depicted in Fig. 4.24. It can be observed that the max von Mises level of 149 MPa was carried out by the CFRP layers to support the concrete beam under flexural loading.

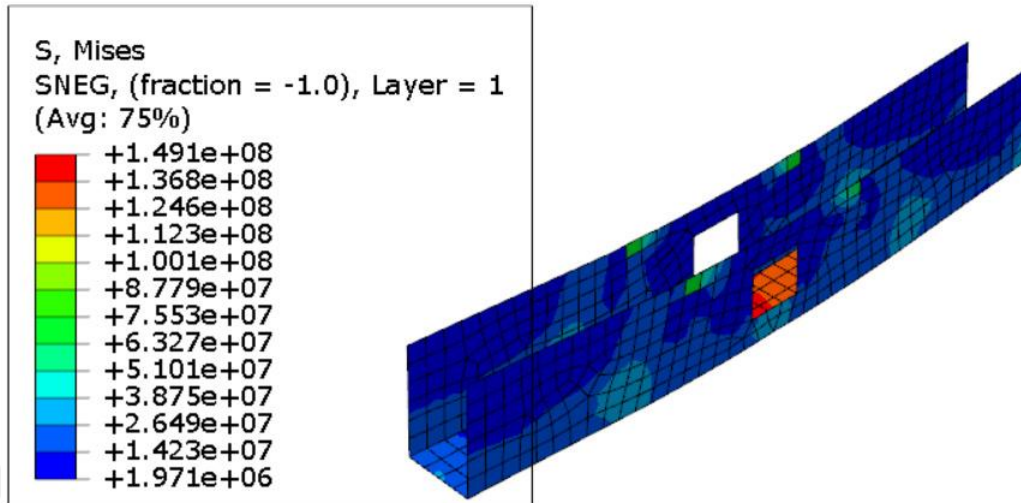


Figure 4.24. The maximum von Mises stress distribution on the CFRP laminates of RCB-CFRP-U-W50.

Fig. 4.25 illustrates the Hashin damage criteria of U shape CFRP after applying the cyclic loading. It can be seen in the figure that the maximum damage has occurred at the bottom of the CFRP at the center where web opening has localized the load on the beam and the maximum load is transferred to the center of the CFRP. On the center of CFRP, the tensile load caused to the damage on the reinforcement.

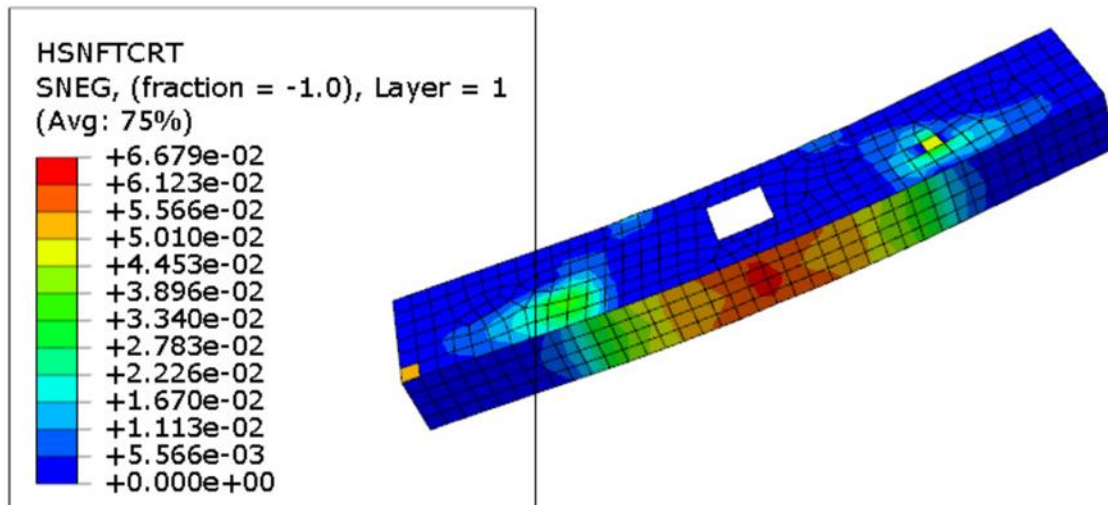


Figure 4.25. Hashin damage criteria (HSNFTCRT) of CFRP reinforcement.

5. FLEXURAL BEHAVIOR UNDER THE THREE-POINT BENDING

The results of the simulations were classified for two different cases of reinforced with BFRP and CFRP laminates. For both classifications two different reinforcement shapes of 1 layer and 2 layers laminates at both sides of the beam. Furthermore, for each classification of the beams with different FRPs, rectangular web openings with different sizes at the center of the beam have been investigated.

5.1 FLEXURAL BEHAVIOR OF REINFORCED CONCRETE BEAM UNDER THE CYCLIC LOADING

An increasing cyclic loading were applied on the beams with the specific time intervals until the failure of the beam. The main concrete part was considered as the important part for the failure. The loading curve is illustrated in Fig. 5.1. Displacement for each cycle were chosen as 1.5 mm. Three rectangular web opening were used with different side sizes of 40%, 60%, and 75% of the width in order to see the effect of web opening size on the flexural behavior of the reinforced concrete beam.

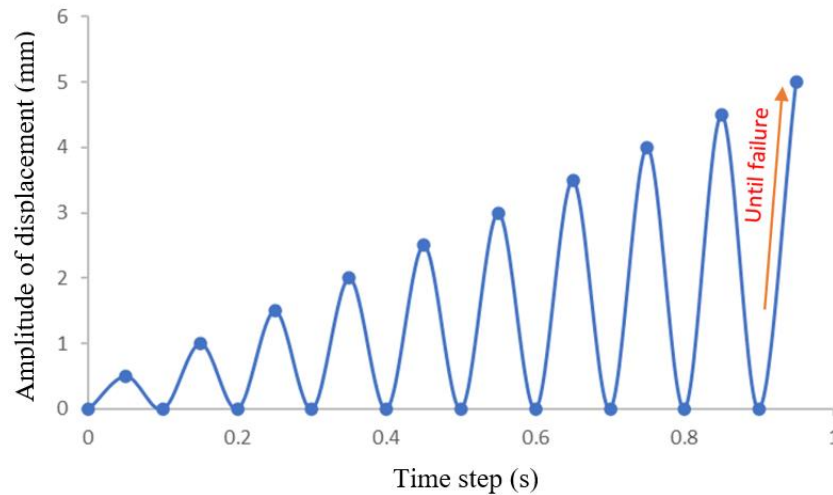


Figure 5.1. Amplitude of cyclic loading in different time steps of simulation.

Fig. 5.2 demonstrates the effect of adding web opening on the flexural behavior of the RC beams with respect to the number of cyclic loading. It can be observed that with increasing the size of the web opening from 40% of the width of the beam to 60%, the maximum von mises stress of the beam has reached to the maximum tensile strength of the beam at lower number of the cycles. Furthermore, stress concentration on the corner of the web opening may significantly decrease the strength of the beam.

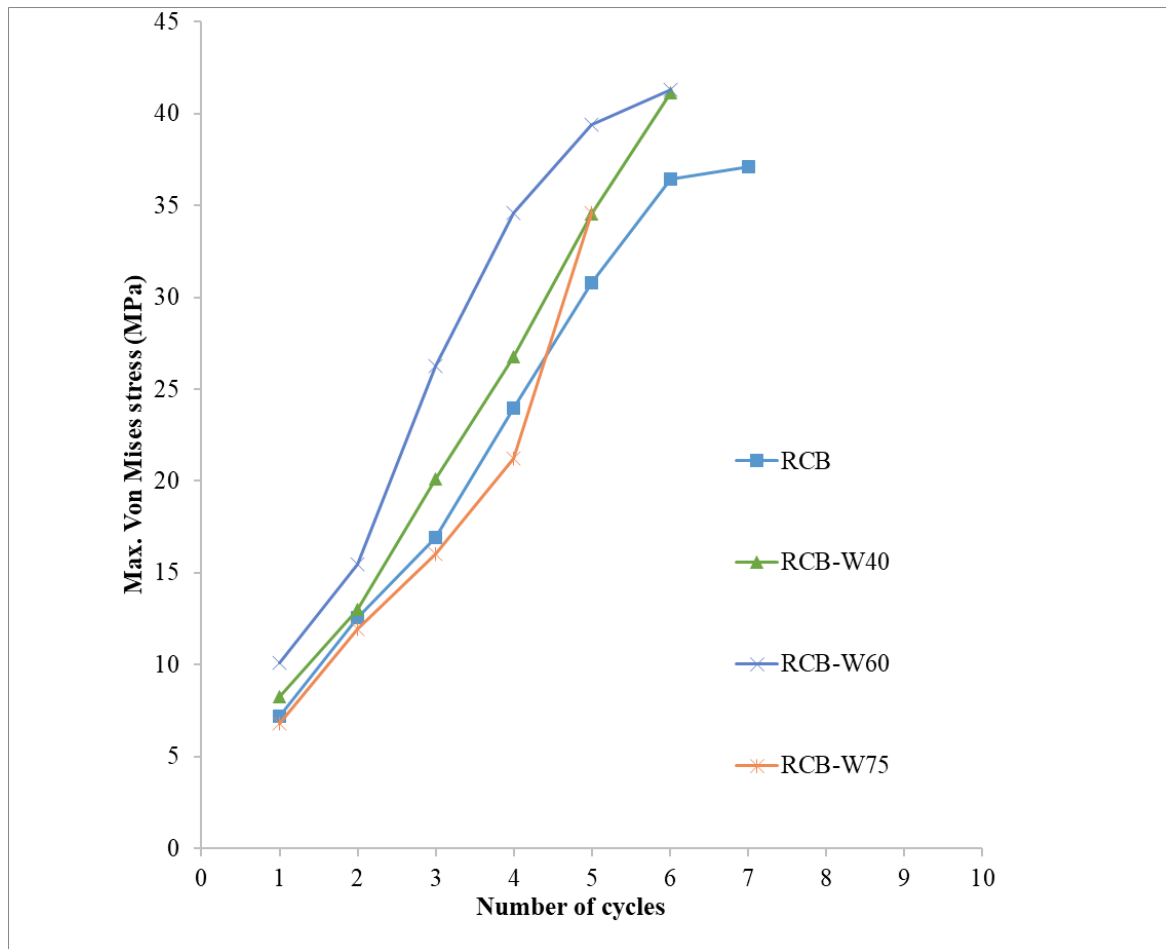


Figure 5.2. Maximum Von Mises stress of the beams with and without web opening at different cycles.

Fig. 5.3 shows the start of the yielding on the concrete beam and increasing the number of the yielded elements throughout that in further cycles with increasing the displacement amplitude. The results of the simulation of the beam were in a good agreement with the literature in case of start of the yielding form the bottom part of the beams and propagating through the sample. Then

with increasing the stress level at further cycles the top parts of the beam was also yield from the compressive stress.

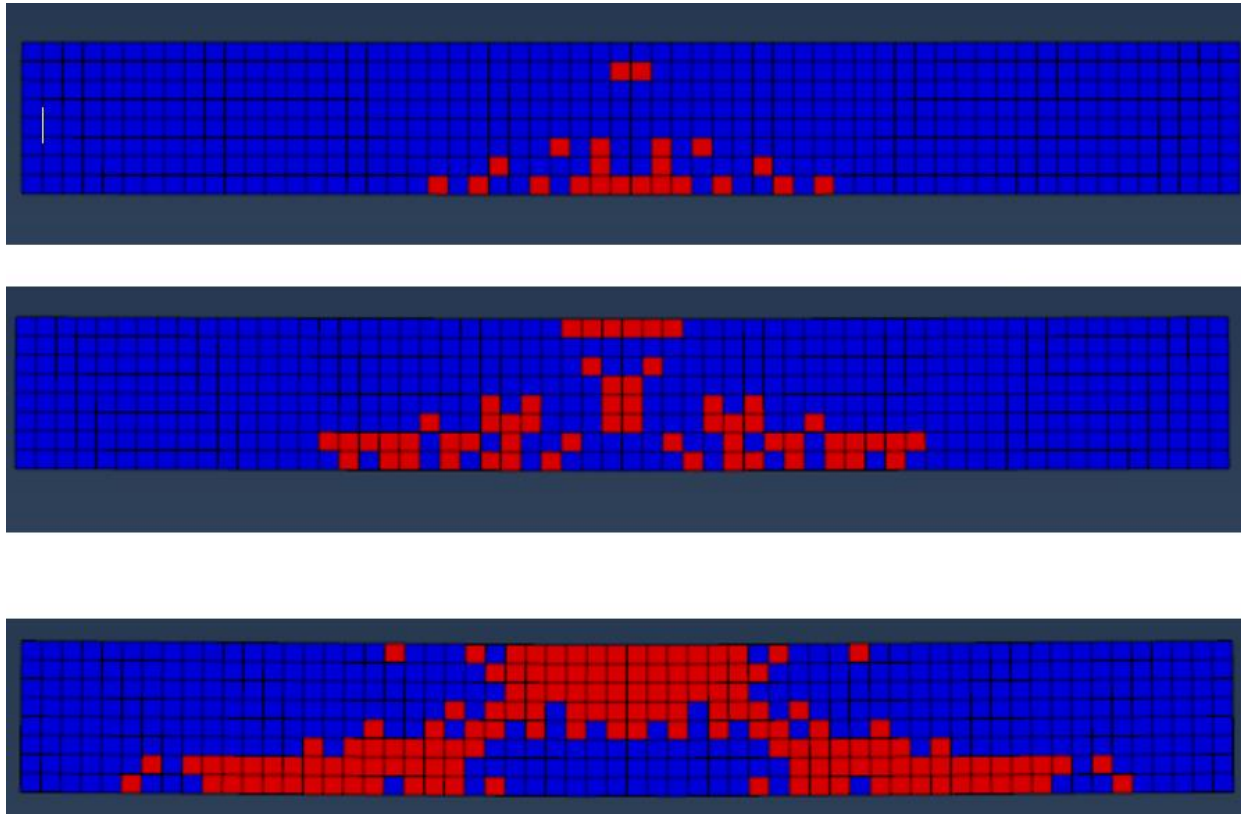


Figure 5.3. Yielding criteria on the RCB during different cycles of loading.

The maximum von Mises stress distribution on the reinforced concrete beam after the fifth cycle was shown in Fig. 5.4. It can be seen that the von Mises stress value has reached to about 40 MPa at the top center of the beam where the displacement has been applied via rigid body.

The equivalent plastic strain on the concrete beam can be seen in Fig. 5.5. In the figure it can be observed that the maximum PEEQ is at the compressive zone at the top of the beam and also at the bottom of the beam where the beam is under the tensile stress.

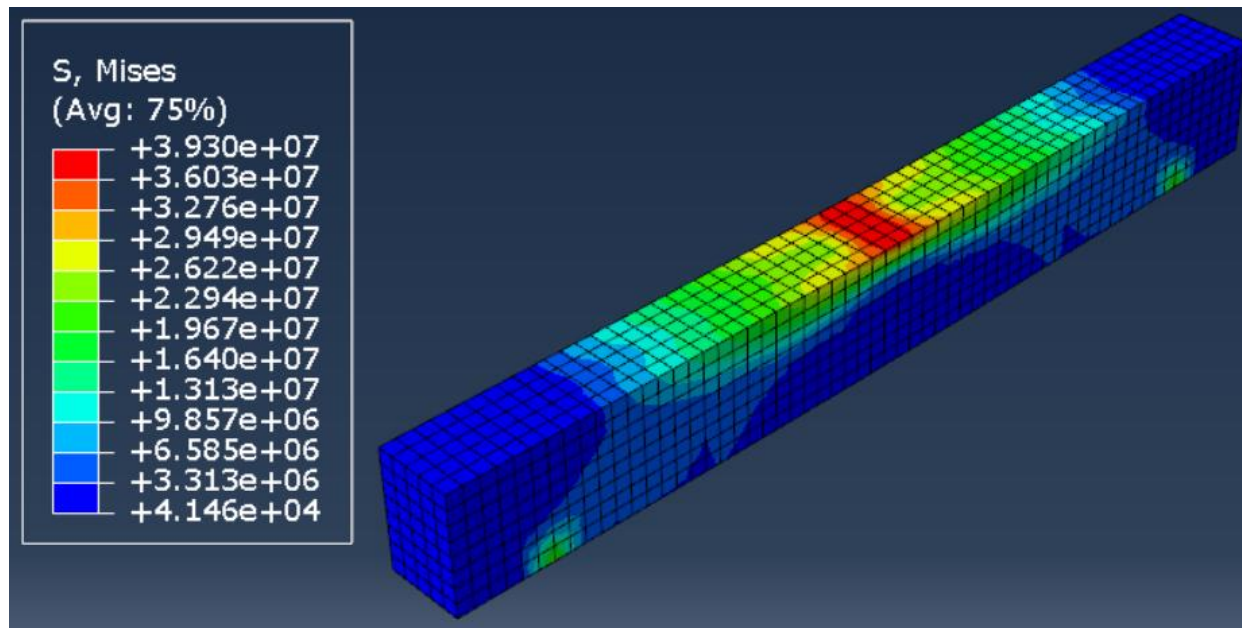


Figure 5.4. The maximum von Mises stress distribution on the reinforced concrete beam after the fifth cycle.

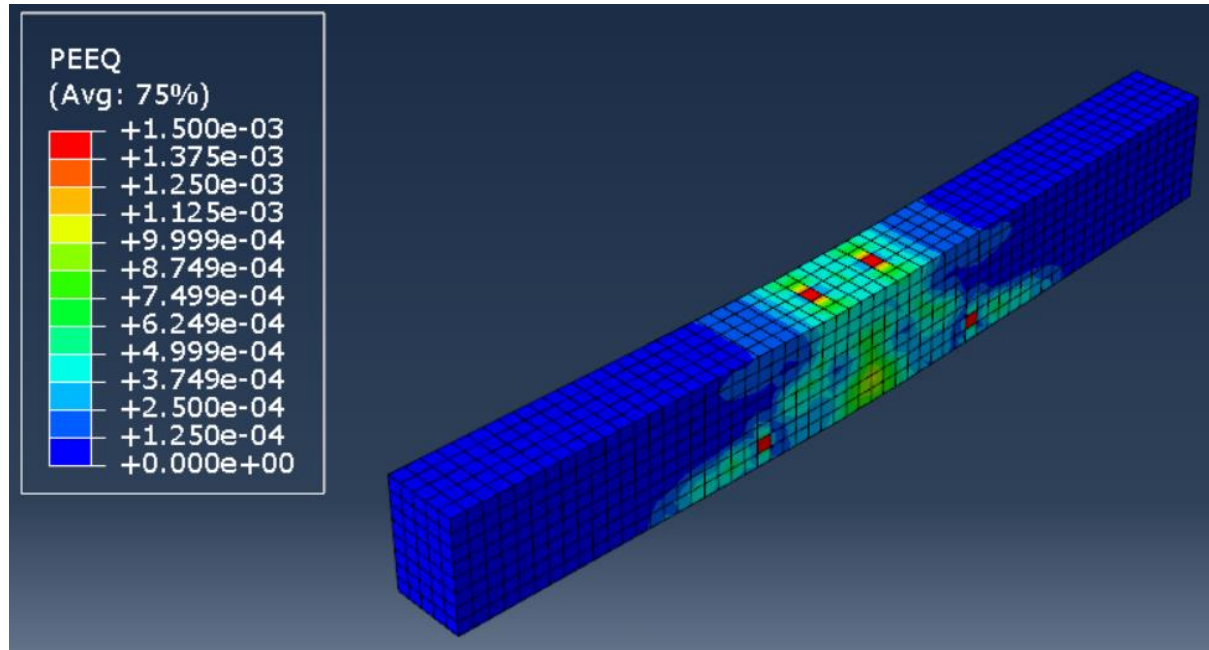


Figure 5.5. The equivalent plastic strain distribution on the reinforced concrete beam after the fifth cycle.

Also, the von Mises stress distribution on the steel bars and stirrups is demonstrated in Fig. 5.6. As shown in Fig. 5.6, the most critical zone on the embedded region was the bottom bars where the maximum stress was 393.2 MPa and that was higher than the yield strength of the steel used in this model.

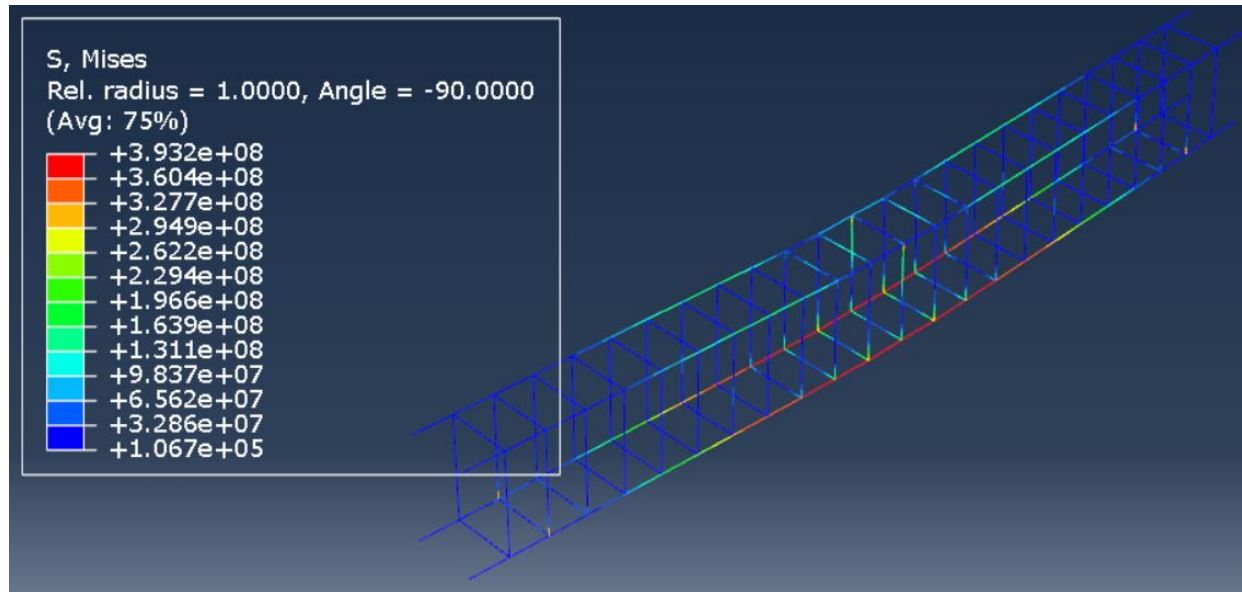


Figure 5.6. The maximum von Mises stress distribution on the reinforced concrete beam.

With the addition of web opening with different ratios of 40%, 60%, and 75%, it can be observed that the level of maximum von Mises stress after each cycle of loading was enhanced due to the stress concentration on the corners of the rectangular web openings and top of the opening. Moreover, with increasing the size of web opening ratio the stress level enhanced and for the 75% web opening the strain was localized on the top of the web opening.

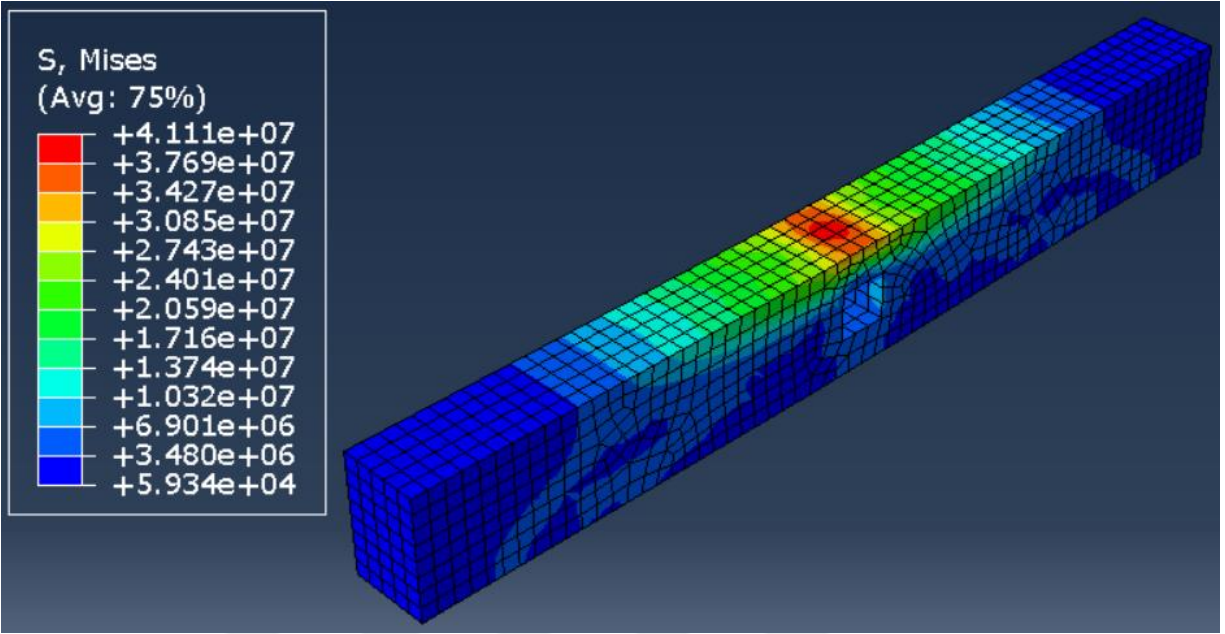


Figure 5.7. The maximum von Mises stress distribution on the RCB-W40 after the sixth cycle.

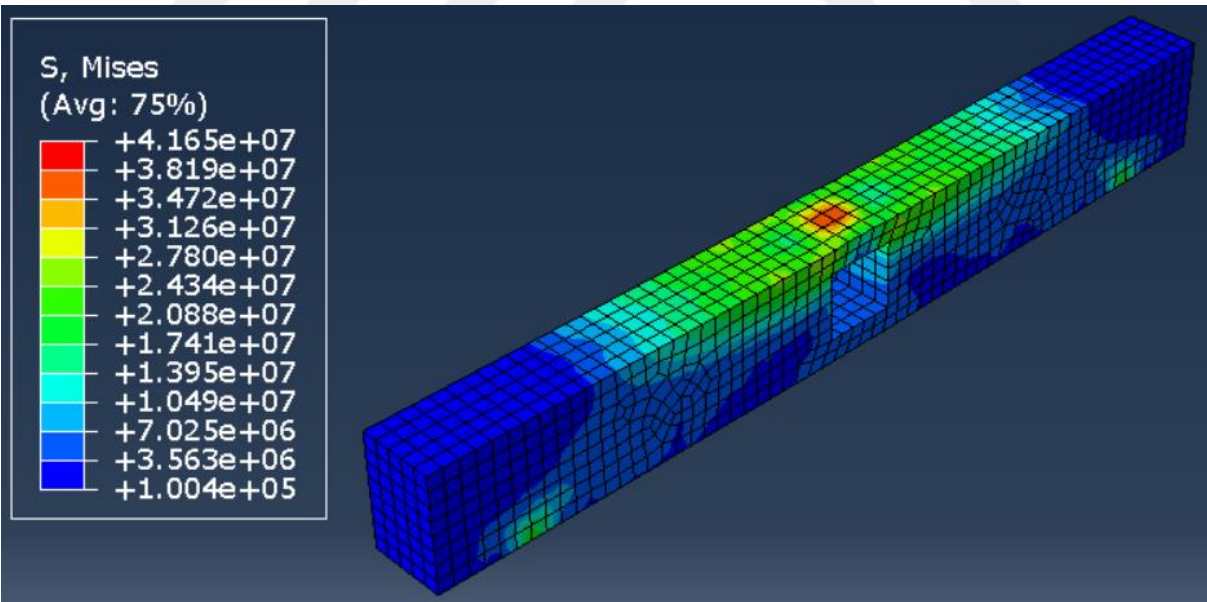


Figure 5.8. The maximum von Mises stress distribution on the RCB-W60 after the sixth cycle.

Regarding the results of the Fig. 5.2, it can be observed that the level of maximum von Mises stress for RCB-W75 is lower than the others approximately at all the cycles. But this is related to

the localization of deformation in this case and this case cannot be applicable for the beams. Fig. 5.9 and Fig 9.10 show the results of equivalent plastic strain and deformation at the 4th cycle for RCB-W75, respectively.

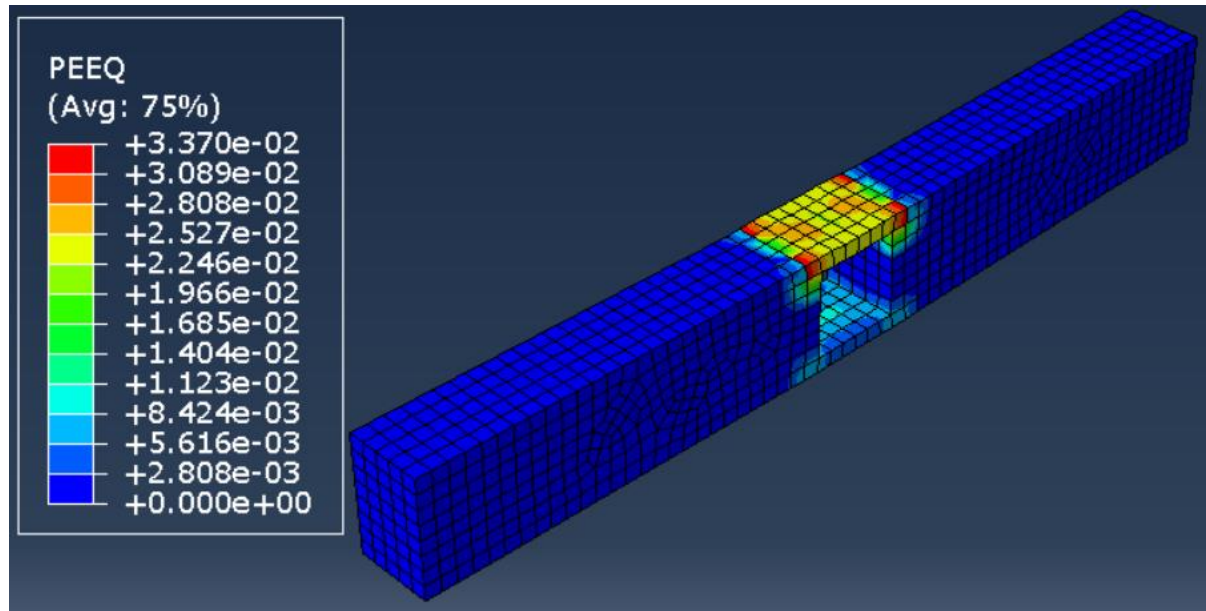


Figure 5.9. The equivalent plastic strain distribution on the RCB-W75 after the fourth cycle.

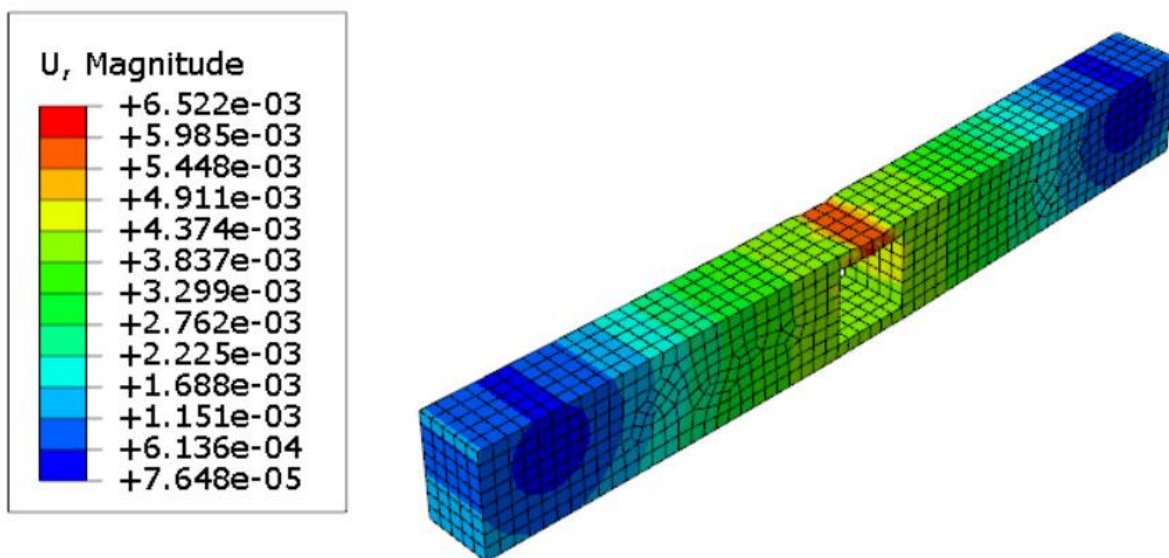


Figure 5.10. Localization of deformation on the top of the web opening part and failure of the RCB-W75 sample.

The Figs. 5.11-5.13 demonstrates the AC yielding criteria of the RCBs with web openings and it can be seen that with increasing the size of the web openings the yielding zone is concentrated around the web opening at the center of the beam.

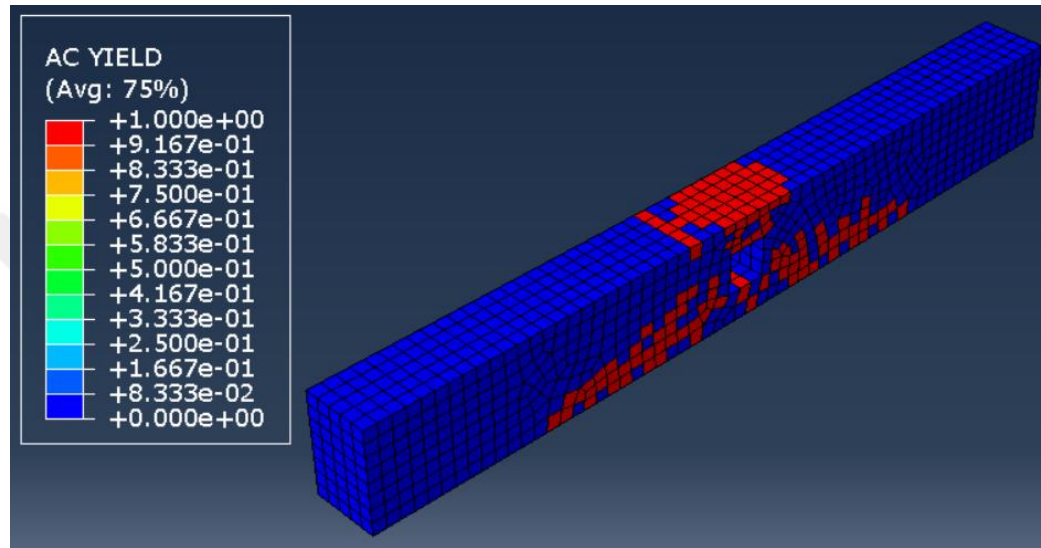


Figure 5.11. Yielding criteria on the RCB-W40.

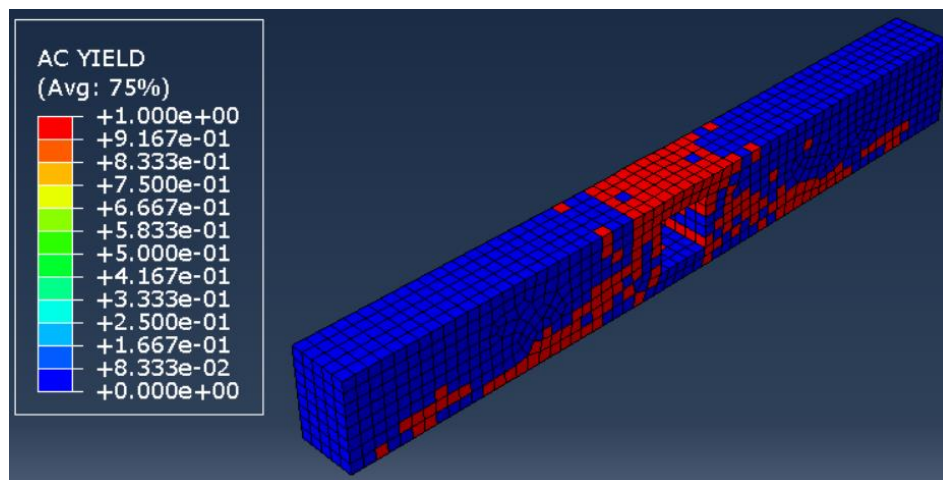


Figure 5.12. Yielding criteria on the RCB-W60.

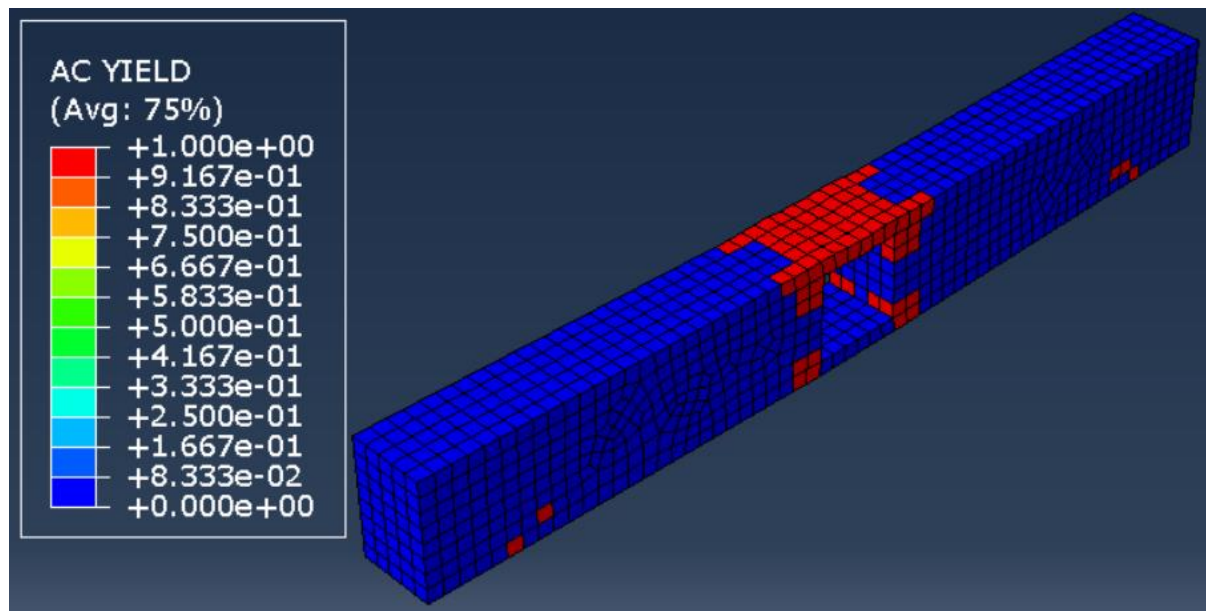


Figure 5.13. Yielding criteria on the RCB-W75.

5.2 FLEXURAL BEHAVIOR OF CFRP REINFORCED CONCRETE BEAM UNDER THE CYCLIC LOADING

CFRP were used to enhance the flexural strength of the system with two different methods. Firstly, 2 layers of CFRP laminates attached to both sides of the beam and then U shape CFRP attached to the reinforced concrete beam to investigate the effect of both reinforcement methods. The mechanical properties of the CFRP defined to the ABAQUS are listed in Table 4.1

5.2.1 Reinforced with 2 layers of CFRP laminates at both side of the beam

The results of the flexural loading simulation of the beam reinforced by CFRP laminates at both sides is demonstrated in Fig. 5.14. With comparing the results of the simulation with 2 Layers of CFRP and without CFRP, it can be observed that for all the cases attachment of the CFRP has decreased the von Mises stress levels of each cycle. Also, considering the web openings with different sizes, it was asserted that the web opening caused to the failure faster than that of the case without the opening.

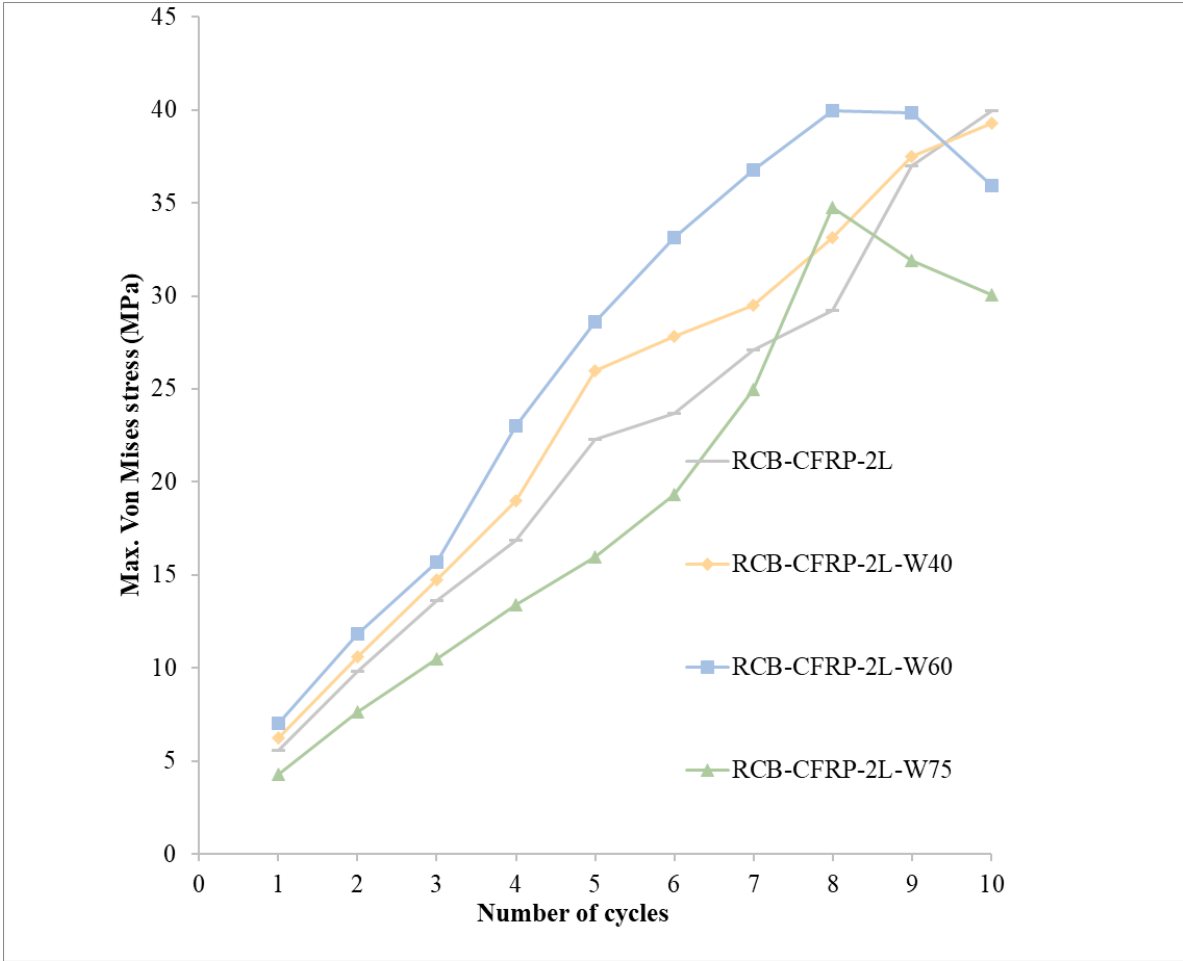


Figure 5.14. Maximum Von Mises stress of the RCB-CFRP-2L with and without web opening at different cycles.

The low level of stress distribution for the RCB-CFRP-2L-W75 in comparison with the others is related to the stress concentration on the top of the web opening and also localization of deformation as it illustrated in Fig. 5.15.

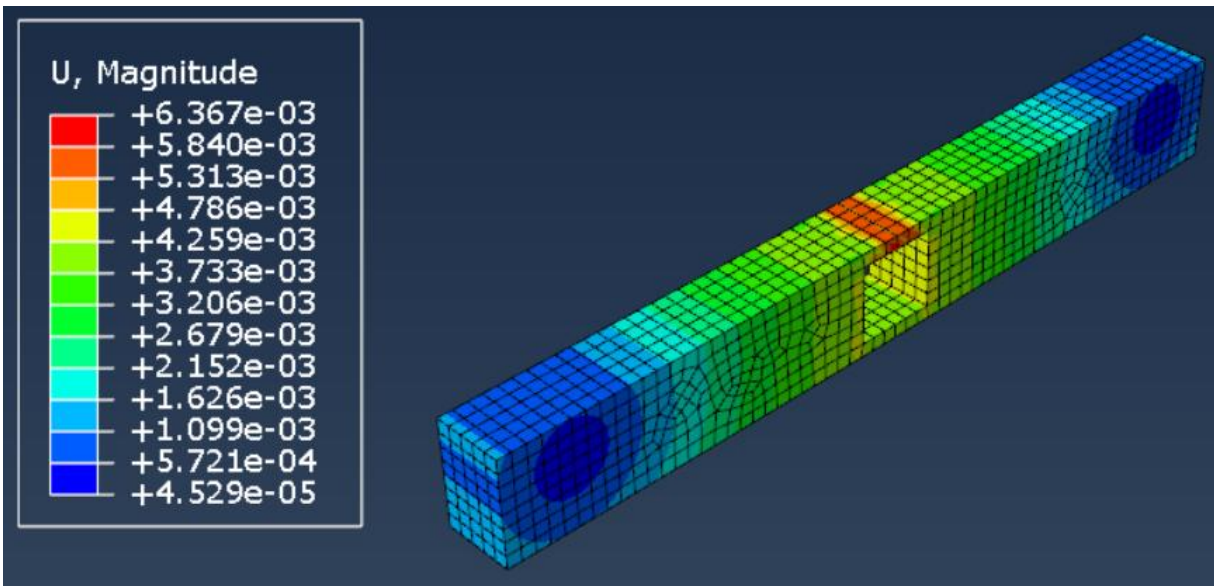


Figure 5.15. Localization of deformation on the top of the web opening part and failure of the RCB-CFRP-2L-W75 sample.

Moreover, the yielding criteria for the beams with different web opening sizes has been demonstrated in Fig. 5.16-5.18. With comparing the results of the simulation for the RCB without the CFRP laminates and with CFRP laminates, it can be understood that the attachment of the CFRP layers has prevented the propagation of yielding to the most parts of the beam and in the beams with web openings it is mostly concentrated around the rectangular web opening sides, top, and corners. Furthermore, with increasing the size of the openings, this yielding becomes more concentrated on the center of the beam (see Fig. 5.18).

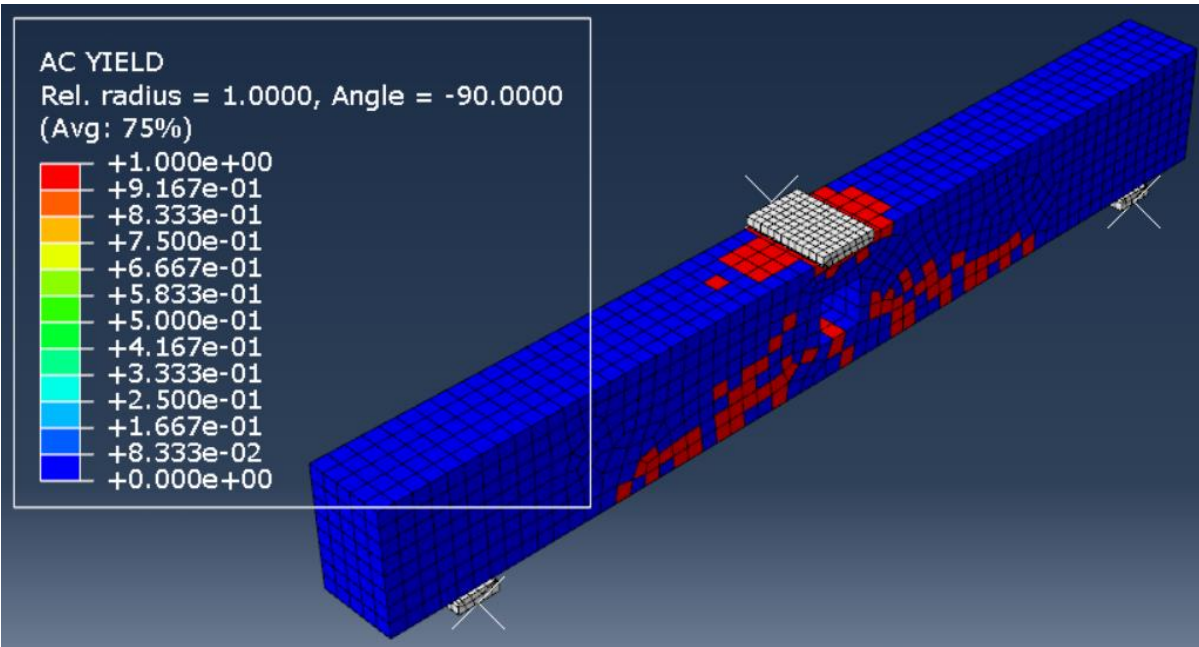


Figure 5.16. Yielding criteria on the RCB-CFRP-2L-W40.

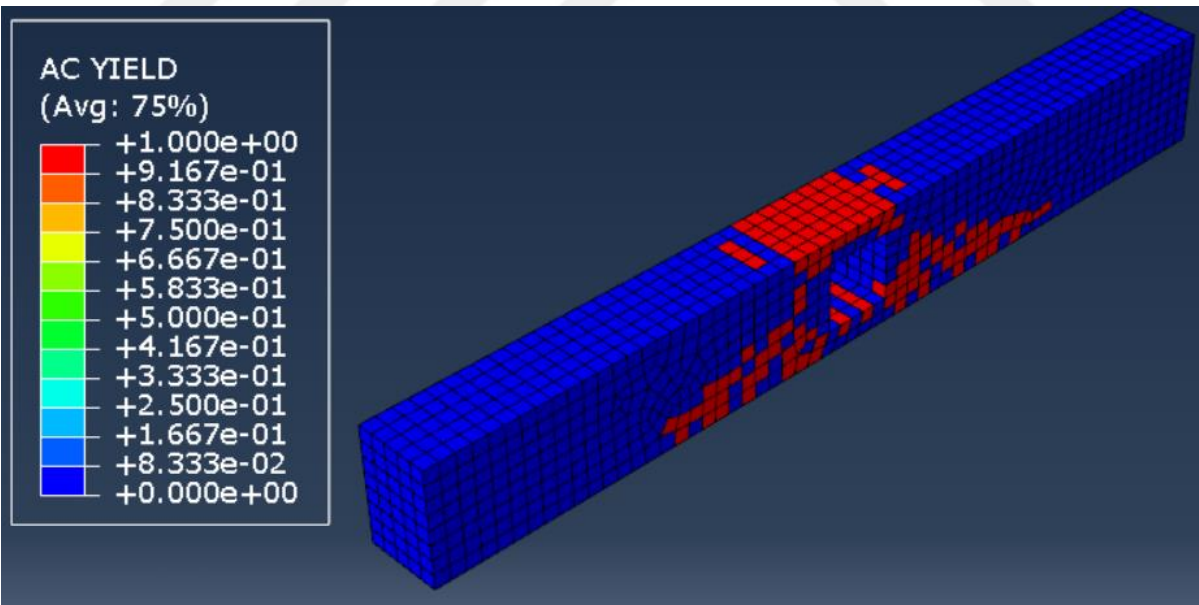


Figure 5.17. Yielding criteria on the RCB-CFRP-2L-W60.

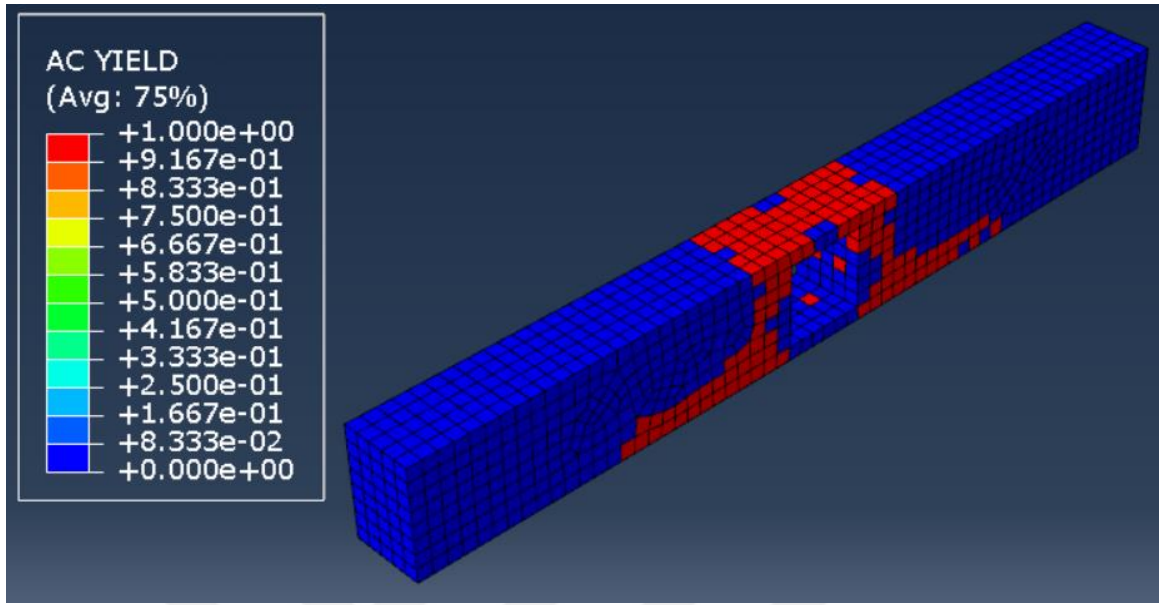


Figure 5.18. Yielding criteria on the RCB-CFRP-2L-W75.

Also, the maximum von Mises stress distribution on the CFRP laminates is depicted in Fig. 5.19. It can be observed that the max von Mises level of 113 MPa was carried out by the CFRP layers to support the concrete beam under flexural loading.

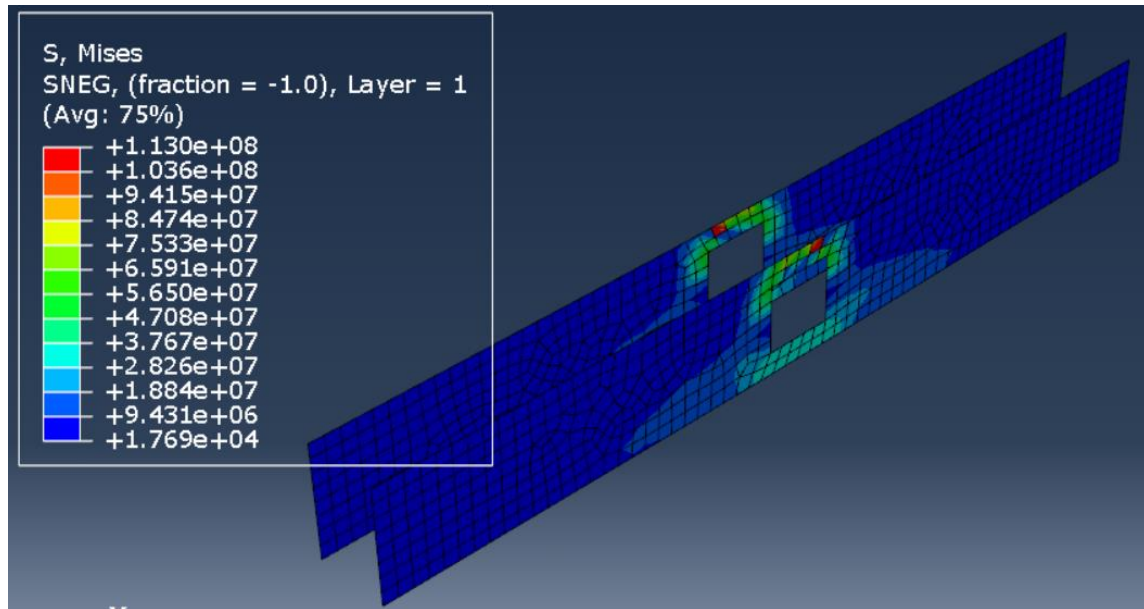


Figure 5.19. The maximum von Mises stress distribution on the CFRP laminates of RCB-CFRP-2L-W60.

5.2.2 Reinforced with U shape CFRP around the beam

U shape CFRP was used to improve the flexural strength of the concrete beam under the cyclic loading. The meshed U shape CFRP is shown in Fig. 5.20.

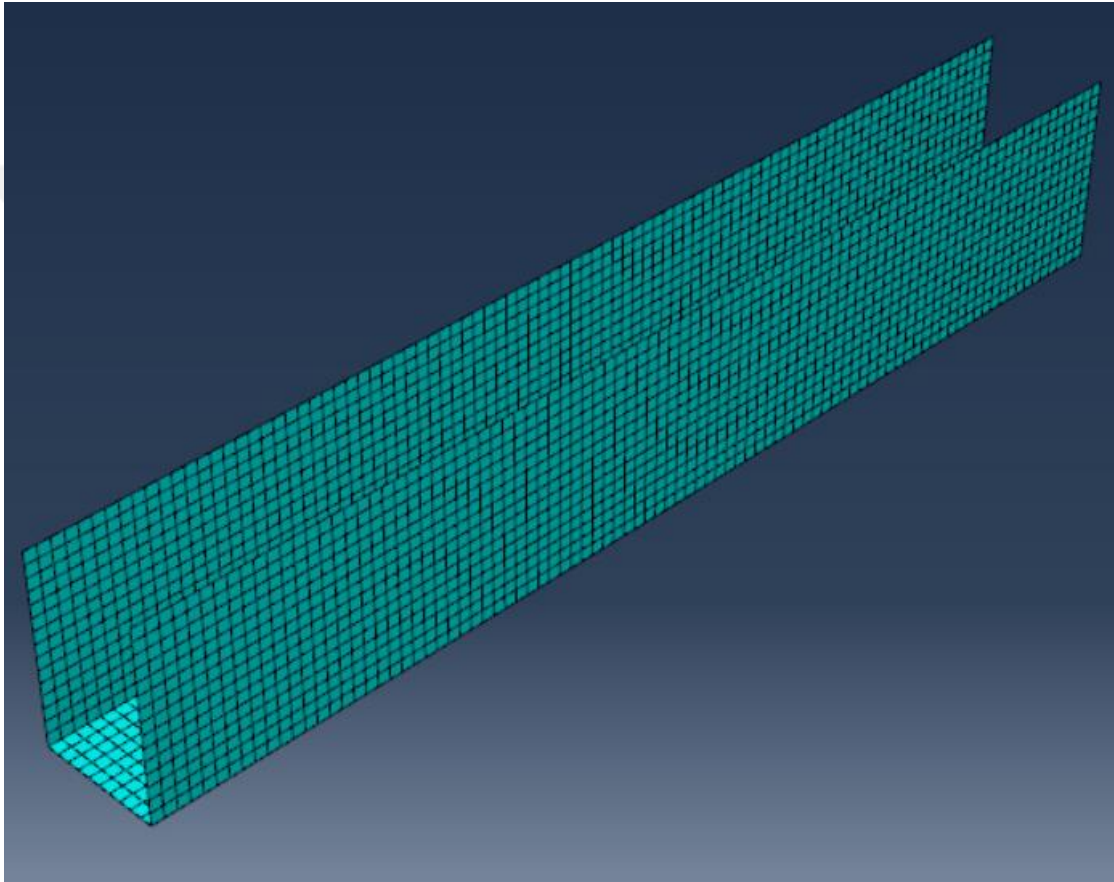


Figure 5.20. Meshed U shape CFRP.

Considering the results of the simulations shown in Fig. 5.14 and Fig. 5.21, it can be seen that the level of maximum Von Mises stress at each cycle for the U shape CFRP reinforced beams are lower than that of CFRP laminates reinforced beams. This is directly attributed to the significant

effect of the bottom layer in U shape CFRP to prevent the initiation of the cracks on the bottom regions of the beam where the beam is under the tensile stress at these parts.

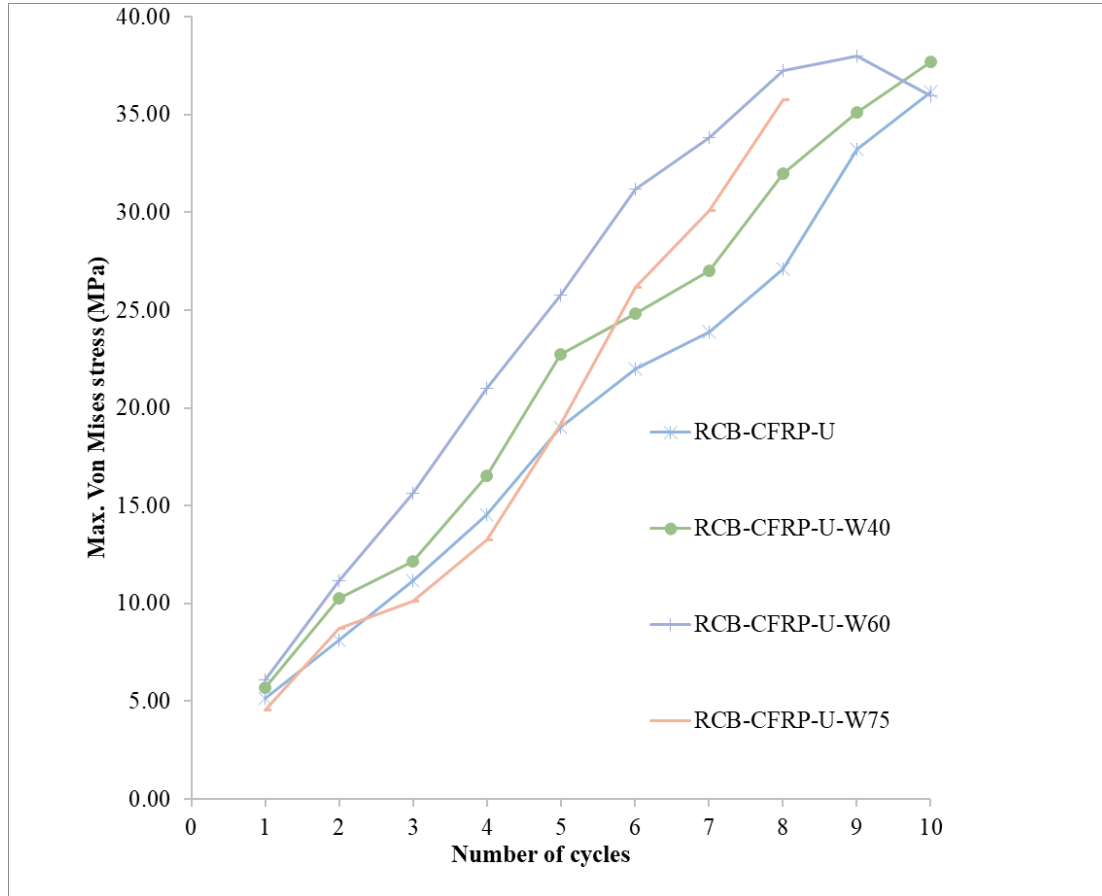


Figure 5.21. Maximum Von Mises stress of the RCB-CFRP-U with and without web opening at different cycles.

Fig. 5.22 demonstrates the stress distribution of the RCB-CFRP-U beam without opening. The results of simulation revealed that the usage of U shape CFRP decreased the stress level on the beam at all the cycles in comparison with the RCB and RCB-CFRP-2L. Also, it can be seen in Fig. 5.22 that although, the maximum stress is at the top center of the beam, the load is more distributed to the other regions due to the attachment of the U shape CFRP to the RCB. After the 8th cycle, still the level of max von Mises stress is lower than 27 MPa after adding U shape CFRP to the beam.

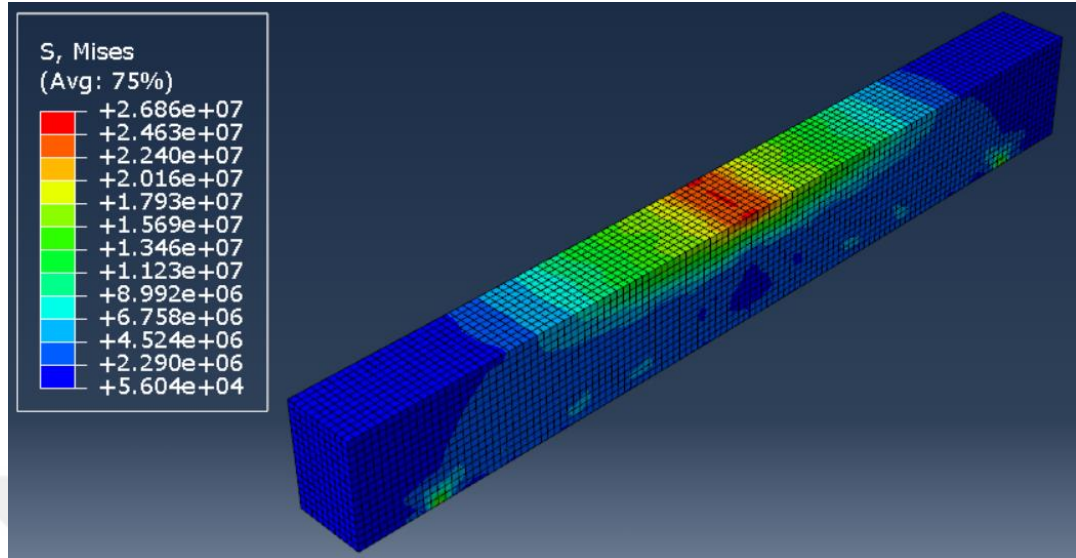


Figure 5.22. The maximum von Mises stress distribution on the RCB-CFRP-U after the 8th cycle.

Also, yielding criteria of the RCB-CFRP-U is shown in Fig. 5.23. It can be observed that the beam started to fail from the bottom sides and top of the beam due to the tension loading and compressive loading, respectively.

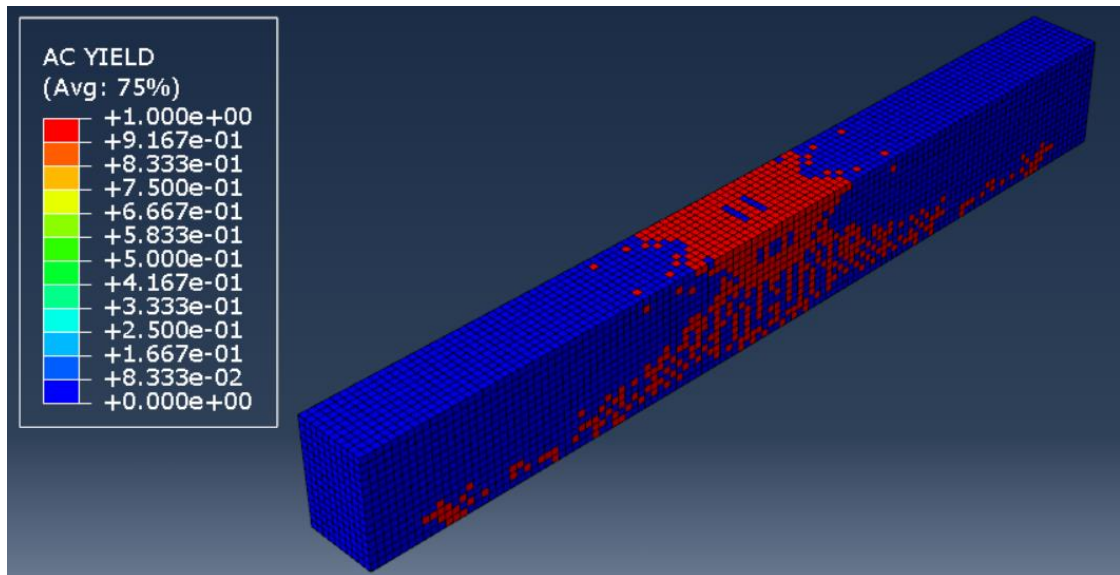


Figure 5.23. Yielding criteria of the RCB-CFRP-U under the flexural loading.

Also, with the addition of the web openings at the center of the beam, the concentration of the yielding on the top region of the openings and also localization of deformation on the center of the beam with 75% web opening is clear in the results of the simulation.

Fig. 5.24-5.26 demonstrates the start of the yielding on the beam at the center of the beam where the web opening with different sizes has been located. Also, it can be seen that with increasing the size of the web opening from 40% to 60% and 75%, the level of concentration on the top of the beam at the center has increased. This can be also related to the low strength of the concrete beam at the center due to the lack of stirrups at this zone where the load is just carried out by steel bars and concrete with the CFRP reinforcement.

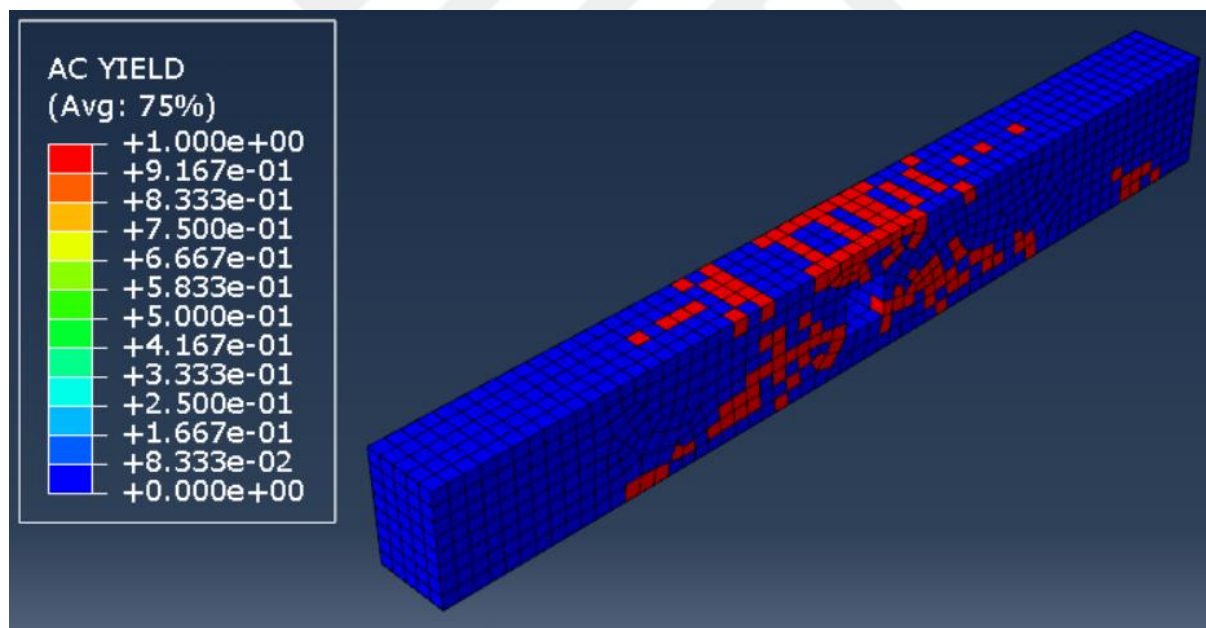


Figure 5.24. Yielding criteria on the RCB-CFRP-U-W40.

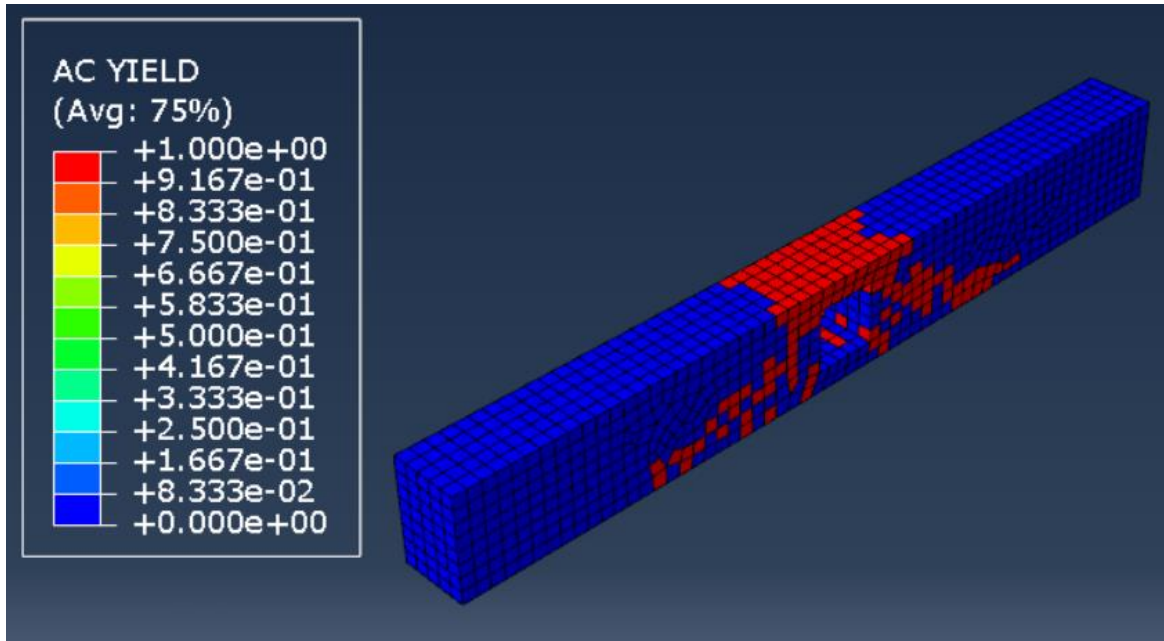


Figure 5.25. Yielding criteria on the RCB-CFRP-U-W60.

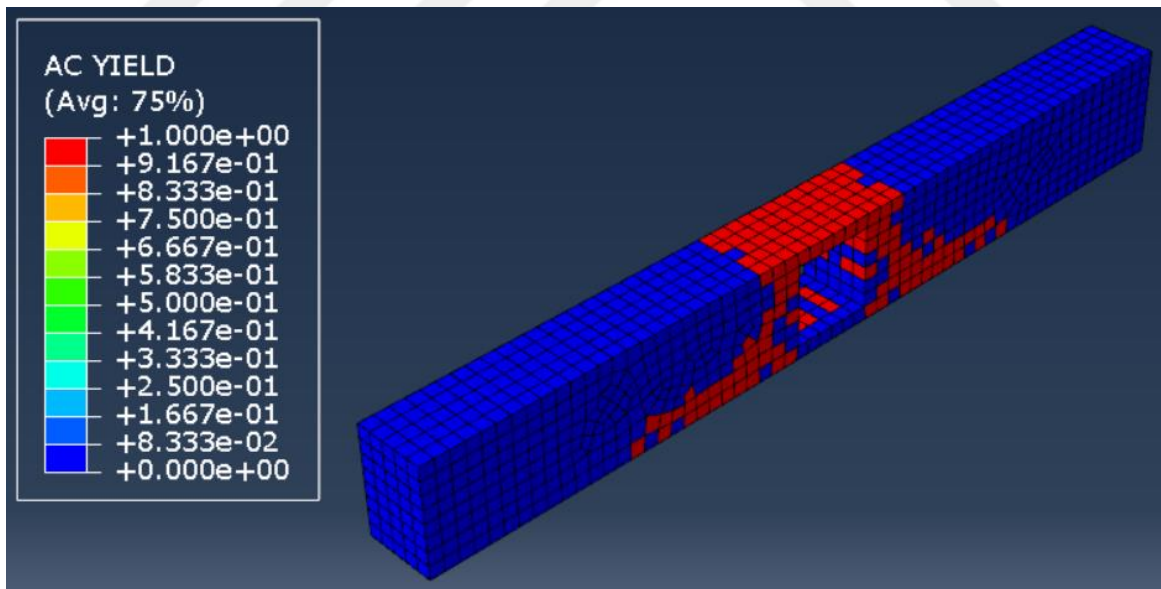


Figure 5.26. Yielding criteria on the RCB-CFRP-U-W75.

5.3 FLEXURAL BEHAVIOR OF BFRP REINFORCED CONCRETE BEAM UNDER THE CYCLIC LOADING

In this section of the study, the effect of adding BFRP laminates to the beam on the flexural behavior has been investigated. The mechanical properties of the BFRP used in this project has been listed in Table 4.2.

Table 5.1. Mechanical properties of BFRP defined to the ABAQUS.

E_1 (N/mm ²)	E_2 (N/mm ²)	ν_{12}	G_{12} (N/mm ²)	G_{13} (N/mm ²)	G_{23} (N/mm ²)
25000	16000	0.25	28000	28000	2650
Longitudinal Tensile Strength (N/mm ²)	Longitudinal Compressive Strength (N/mm ²)	Transverse Tensile Strength (N/mm ²)	Transverse Tensile Strength (N/mm ²)	Longitudinal Shear Strength (N/mm ²)	Transverse Shear Strength (N/mm ²)
580	280	100	150	100	100

As demonstrated in Fig 4.27, it can be observed that the positive effect of the BFRP laminates enhanced the flexural strength of the beam at different cycles of the loading. Therefore, the concrete beams have reached to the failure stress level of 35 MPa at the 9th or 10th cycle for different web opening sizes. However, the beam with 75% web opening size has failed after the 6th cycle due to the localization of the deformation on the top part of the web opening and stress concentration on that region.

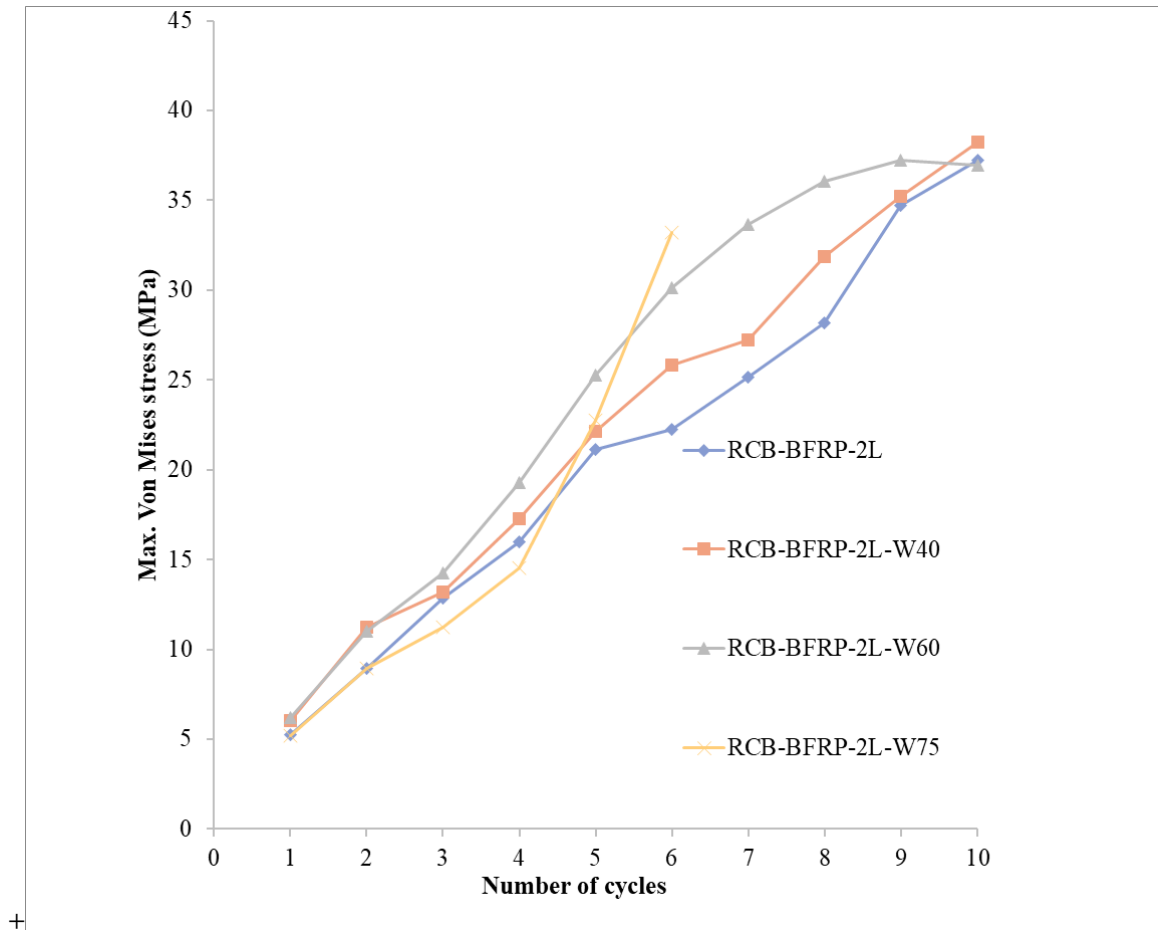


Figure 5.27. Maximum Von Mises stress of the RCB-BFRP-2L with and without web opening at different cycles.

6. CONCLUSIONS

In the current thesis, the effect of CFRP and BFRP laminates on the cyclic flexural behavior of RC beams were investigated using ABAQUS software. Four-point bending setup for CFRP and three-point bending setup were designed and simulated for both CFRP and BFRP. Furthermore, the effect of web opening with different sizes were analyzed and the highlights of the results are as follow:

- a. Two layers CFRP and BFRP laminates increased the flexural strength of the RC beams under cyclic loading significantly.
- b. With changing the shape of the CFRP laminates to a U shape CFRP layer, the number of cycles to failure were increased and von Mises stress level at each cycle were also decreased. This can be related to the effect of the bottom layer to prevent the failure of the concrete from the bottom where the beam is under the tensile stress.
- c. With increasing the size of the web opening, the flexural strength of all RCB, RCB-CFRP and RCB-BFRP was decreased gradually. Moreover, deformation localization was seen on the samples with 75% web opening size which caused to the failure of the beam at earlier cycles.
- d. All beams yield from the bottom parts due to the lower strength of the concrete against the tension loading. However, with adding web openings to the beams, the stress concentration was occurred on the edges and top of the web opening.
- e. In four-point bending method, after the fifth cycle the von Mises stress of RCB-W60 was about 18% higher than that of RCB while the stress level after the fifth cycle for the RCB-CFRP-U-W60 was 10% higher than that of the RCB-CFRP-U without web opening. This can be attributed to the fact that CFRP reinforcement decreases the stress concentration on the web opening regions.
- f. The results of Hashin damage criteria (HSNFTCRT) of CFRP reinforcement for the RCBs reinforced with U shape CFRP revealed that the most critical region for the failure of the CFRP layer is the bottom of the U wrapped shape and the edges around the loading rigid bodies.

7. FUTURE WORKS

In this study, the effect of CFRP and BFRP reinforcements on the RCBs have been investigated via simulation of four-point and three-point bending tests under the cyclic loading. Despite the different experimental and numerical investigations have been done on the flexural behavior of the RCBs, there are many cases related to the reinforcement of the FRPs on the beams and different size of the web openings which need to be investigated. Some recommendations for the future works are listed as follows:

- a. Using different FRPs with various shape on RCBs to compare the mechanical behavior and investigating the damage behavior experimentally and numerically.
- b. Investigation of FRP thickness on the supporting effect of the RCBs.
- c. Analysis of mesh size effect in ABAQUS.
- d. Investigation of crack initiation and propagation on the RCB with and without FRPs.
- e. Web opening shape effect on the flexural strength of the RCBs.

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