ADDIS ABABA UNIVERSITY

ADDIS ABABA INSTITUTE OF TECHNOLOGY

SCHOOL OF CIVIL AND ENVIRONMENTAL ENGINEERING

SHEAR STRENGTHENING OF REINFORCED CONCRETE DEEP BEAMS WITH OPENINGS USING GLASS FIBER REINFORCED POLYMER (GFRP) COMPOSITES

A Thesis in Structural Engineering

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The undersigned have examined the thesis entitled '**Shear Strengthening of Reinforced Concrete Deep Beams with Openings Using Glass Fiber Reinforced Polymer (GFRP) Composites**' presented by **Seare Tekie Mebrahtu**, a candidate for the degree of **Master of Science** and hereby certify that it is worthy of acceptance.

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UNDERTAKING

I certify that research work titled “Shear Strengthening of Reinforced Concrete Deep Beams with Openings Using Glass Fiber Reinforced Polymer (GFRP) Composites” is my own work. The work has not been presented elsewhere for assessment. Where material has been used from other sources it has been properly acknowledged / referred.

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ABSTRACT

Reinforced concrete deep beams are structural elements loaded as simple beams in which large amount of the load is transferred to the supports by a compression force connecting the load and the reaction. These beams are widely used as transfer girders, foundation walls, walls of bunkers and load bearing walls. Utility pipes and ducts are necessary to accommodate electrical and mechanical services including air conditioning, power supplies, telephone cables, computer accessories, sewerage lines and water supply. The provision of opening holes in the web of a reinforced concrete deep beams causes many problems in the beam behavior such as reduction in the beam stiffness, excessive cracking, excessive deflection and reduction in the beam strength. Enlargement of such openings due to electrical or mechanical requirements would reduce the element's shear capacity. When such enlargement is unavoidable, adequate measures should be taken to strengthen the beam and counteract the strength reduction. In this study an experimental investigation on the strengthening of reinforced concrete deep beams with circular and square openings is conducted. A total of nine specimens with circular and square openings are constructed and tested under point loading. The test specimen has a cross section of 100 x 500mm and a total length of 1050mm. Two circular or square openings, one in each shear span, are placed symmetrically about the mid-point of the beam. Externally bended glass fiber reinforced polymer (GFRP) shear strengthening on the beam was found very effective in upgrading the shear strength of the reinforced concrete deep beams. It was found that externally bonded GFRP is very effective to enhance the shear strength of the RC deep beams. The strength gain caused by the application of GFRP was in the range of 37% - 66% as compared to the load carrying capacity of un-strengthened deep beams.

Key words- deep beams, glass fiber reinforced polymer, strengthening.

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ABBREVIATIONS

ACIAmerican Concrete Institute

CFRP Carbon Fiber Reinforced Polymer

FRP Fiber Reinforced Polymer

GFRP Glass Fiber Reinforced Polymer

HSC High Strength Concrete

RC Reinforced Concrete

NOTATIONS

A_s	Area of reinforcement
$A_{s\text{-}min}$	Minimum area of reinforcement
$A_{v\text{-}min}$	Minimum vertical stirrups
$A_{vh\text{-}min}$	Minimum horizontal stirrups
A_s+	Positive reinforcement
A_s-	Negative reinforcement
f_y	Characteristic strength of reinforcement
f'_c	Concrete cylinder strength
j_d	Lever arm
b	Width of the beam
D	overall depth of the beam
d	Effective depth
L_n	Effective length
M_u	Moment of resistance
S_v	Spacing for vertical shear reinforcements
S_h	Spacing for horizontal reinforcements

DEDICATION

I dedicate this thesis to my beloved father **TEKIE MEBRAHTU** and my beloved mother **HAREGEWEINI WELDEMARIAM**, who poured me the spirit of hard working. May their soul rest in peace.

CHAPTER 1 INTRODUCTION

1.1 DEEP BEAM

Reinforced concrete deep beams are structural elements loaded as simple beams in which large amount of the load is transferred to the supports by a compression force combining the load and the reaction.The construction of large buildings is different from the construction of smaller buildings. In the construction of large buildings, the beams at the lower part will carry larger loads when compared with the beams in smaller buildings.

A reinforced concrete deep beam may be defined as one whose depth is comparable to its span and the main factor affecting the definition of reinforced concrete deep beam is span-depth ratio. The ACI code (ACI-318-02)[1] defines beams with clear span to effective depth ratios (Ln/d) less than four as deep beams, whereas the European standard (EN 1992-1-1)[2] treats deep beams having span to depth ratios less than three.

The deep beam has a larger depth because it is a load transferring structural component which is usually used to transferring a great amount of loads from above to supports at below. Deep beam usually used in the construction of high-rise buildings as a transfer girder. Reinforced concrete deep beams are widely used as transfer girders in offshore structures and foundations, walls of the bunkers, concrete shear wall and load bridge construction.

In the construction of modern buildings, there are mechanical, electrical and passage ways such as services including air conditioning, power supply, telephone line, computer network, sewerage and water supply that need to be consider during the construction process. Transverse openings are often provide through beams for the passage of utility ducts and pipes.These opening holes can be of different shapes and sizes as circular, square or rectangular.These openings have a significant effect on the structural capacity of existing member. To address such situations, strengthening material such as a glass fiber reinforced polymer (GFRP) is used to strengthenthe beams externally.

In this study an experimental investigation on the strengthening of reinforced concrete deep beams with circular and square openings is conducted. The strength gain caused by the application of GFRP was in the range of 37% - 66%.

1.2 PROBLEM STATEMENT

The openings on a structural element were made for mechanical and electrical purposes. From the view point of a structural engineer, there are some difficulties to make decision when the openings are required to be made on the reinforced concrete deep beams. This is because there is no code of design for deep beams with openings. The openings may reduce the strength of the RC deep beam will lead to structural failure.

The presence of web openings in such beams is frequently required to provide accessibility such as doors and windows or to accommodate essential services such as ventilating and air conditioning ducts. Enlargement of such openings due to mechanical or electrical requirements and/or a change in the buildings function would reduce the elements shear capacity, thus rendering a sever safety hazard. The presence of an opening in the web of reinforced concrete deep beams lead to many problems in the beam behavior such as reduction in the beam stiffness, excessive cracking, excessive deflection and reduction in the beam strength. Furthermore, sudden change in the dimension of cross section of the beam lead to high stress concentration at around and corners of the openings that may cause to cracking unnecessary from aesthetic and durability viewpoints. Limited studies have been reported in the literature on the behavior and strength of RC deep beams with openings. It was concluded that increasing the opening size would result in a significant reduction in the shear strength. When such enlargement is unavoidable, adequate measures should be taken to strengthen the beam and counteract the strength reduction.

Therefore, special strengthening should be provided on the RC deep beam with openings to prevent possible cracks and failure of the beam.

1.3 RESEARCH OBJECTIVES

The main objective of this study is shear strengthening of reinforced concrete deep beams with openings using glass fiber reinforced polymer (GFRP) composites with regard in experimental testing of beam with and without GFRP.

Specific objectives of this study will be:

i. To study the behavior of the RC deep beam with openings under two circumstances; the first circumstances is the RC deep beam without GFRP strengthening, the second circumstances is the RC deep beam with GFRP strengthened in shear, in terms of load-deflection behavior and crack patterns.
ii. To determine the effects of the shape and size of openings on the RC deep beam.
iii. To identify the most effective strengthening method from the various methods of strengthening regarding previous researches.

1.4 METHODOLOGY

The methodology worked out to achieve the above-mentioned objectives is as follows:

i. Review the existing literature and American Concrete Institute (ACI 318) [1] provision for designing the deep beam.
ii. Adopting a mix design of C-30 grade concrete (as per ACI 318) [1] to construct the deep beam with circular and square openings.
iii. A total of nine beams were casted along with 3 cubes each for a beam.
iv. Un-strengthened and strengthened beams are tested under single point loading after 56 and 57 days curing and the cubes after 28 days to determine the compressive strength of concrete.
v. The control beam and other four beams with circular and square openings are tested in their initial condition and remaining 4 beams were strengthened using glass fiber with 3mm thick layer to determine the maximum strength condition.

1.5 SCOPE OF STUDY

In this study the dimensions of the reinforced concrete deep beam models were 1050mm length, 100mm width and 500mm depth. A total of nine models were casted for experimental study. A solid deep beam named as CB, which is functioned as control beam or a reference of the study was used as controlling model, which is a reinforced concrete deep beam without any opening. There are 8 models with openings were casted. There were different in size of openings, 110 and 160mm diameter for circular openings and 110x110mm and 160 x 160mm for square openings. The supports are located at 90 mm from both edges of the deep beams whereas the loading point is 525mm from both edges of the deep beam.

The GFRP used to apply on the RC deep beams was cut into different size according to the dimension of the area applied. All the GFRP sheets were applied on four deep beams having openings in order to resist the natural load path of diagonal cracks within the shear zone.

1.6 SIGNIFICANCE OF RESEARCH

From the previous literature reviews, most researches show that the beam capacity of the reinforced concrete (RC) deep beams is reduced with the existence of the web openings. A good deal of studies and researches have been done regarding to the openings in deep beams in the last past few years. As the people realized the usage of deep beams increases, it becomes vitally important to study the behavior of these beams in different circumstances. There are some main factors included in the issue stated in previous research such as concrete strength used, shear span-to-depth ratio of the beams, cross-sectional properties, configuration and type of web reinforcement, size, shape and location of web opening. Therefore, this research would provide the experimental results and information towards the behavior and ultimate capacity gained of RC deep beam with opening strengthened by the application of GFRP. At the same time, this study also compensates the loss of deep beams' shear strength caused by creation of large openings. Last but not least, highest effectiveness percentage or most effective strengthening method would be provided in this study, thus it can be used in future construction industry. The results and conclusions are intended to be useful for further structural engineering practice.

1.7 ORGANIZATION OF THESIS

Chapter 1 gives a brief introduction to the concept of deep beam and deep beam with openings and its uses. The importance of fiber reinforced polymer in strengthening of concrete structures and the advantages and disadvantages of GFRP the need for present work and also the objective of the project is presented in this chapter.

Review of literature on deep beams and methodology of the proposed work have been presented in Chapter 2.

Chapter 3 deals with the design stipulations of deep beam in general. An example with detailed reinforcement diagrams is also explained in this chapter.

Chapter 4 presents the detailed experimental study. Testing of all the beams with different GFRP systems is also been covered in this chapter.

Chapter 5 deals with the results and discussions which cover different failure modes observed, load deflection analysis and ultimate load carrying capacity of all the beams.

Chapter 6 deals with the conclusions and the recommendation for the future work.

CHAPTER 2 REVIEW OF LITRATURE

2.1 GENERAL

The construction of large buildingsare different from the construction of a smaller buildings. In the construction of the large buildings, the beams at the lower part will transfer large amount of loads when compare to those smaller buildings. Deep beams are structural elements loaded as simple beams in which a large amount of the loads from the upper part of the building is carried to the supports by a compression force combining the load and the reaction.

The provision of larger size of deep beam will not allow the passage to mechanical and electrical lines.In this case, these lines have to pass through the deep beams. It has been practiced that these lines are usually placed at the bottom face of the beams, and covered by a roof ceiling. This arrangement of building can be a cause to a significant reduction in the dead space and more complex design. The solution to solve this problem is providing openings at the beam. These openings are required for the passage utilities lines and ventilation ducts.

There are two main types of openings in the construction of buildings, pre-planned and post- planned openings. Parameters such as shape, size,orientation, etc. in openings are well known at the design stage are known as pre-planned openings. In this case, the design of internal strengthening around the opening is considered during the design stage. In post-planned openings,existing structural elements such as beams may need penetrating of holes. These holes have a significant effect on the structural capacity of existing member. To avoid such problems, strengthening techniques such as a glass fiber reinforced polymer (GFRP) is used to strengthen the beams externally. This method can be applied for the strengthening of deep beams and other such structural elements which are affected during the penetrating process.

2.2 GLASS FIBER REINFORCED POLYMER

FRP can be applied to strengthen the beams, column and slabs of buildings and bridges. It is possible to increase the strength of structural members even after they have been severely damaged due to the loading conditions. In case of damaged reinforced concrete members, this would first required the repair of the member by removing loose debris and filling in cavities and cracks with mortar or epoxy resin. Once the member is repaired, strengthening can be achieved by impregnating the fiber sheets with resin then applying them to the cleaned and prepared surfaces of the member.

Non-metallic fibers, such as carbon and glass fibers encapsulated in a polymer matrix in the form of wires, bars and strands have shown great potentials as reinforcement for concrete. It is commonly known as fiber reinforced polymer or FRP.

Glass fibers, also known as 'fiber glass', are most extensively use reinforcements for polymer composites due to their combination of low cost, high strength and relatively low density. Unlike carbon fibers, glass fibers are isotropic thus avoiding loss of properties when loaded in the transverse direction. Fiber glass is produced by pulling molten glass through orifices at a temperature where the glass has just the right amount of viscosity.

2.2.1 Gelcoat

Gelcoat or 'Gel Coat' is a material used to provide a high quality finish on the visible surface of a fiber reinforced composite. Gel coating of open molds is often the first and final part in the production process. The material is highly pigmented form of unsaturated polyester resin which can be pigmented to the desired product. But gel coat alone does not have the structural strength to be removed from the mold or to be used as a final product, so another material must be added for reinforcement. This second step in the process is called lamination.

2.2.2 General purpose resin or G.P Resin

It is a quick curing unsaturated polyester material for laminating purpose. It is un-accelerated. Suitable for both hand layup and gun spray up. The resin offers excellent mechanical properties, impact and water resistance. The fiberglass laminate made with this resin has excellent mechanical strength, good rigidity and durability. G.P resins areused in all types of composite construction. The general purpose polyester resins performs best if the laminate is completely post cured. The quality of catalyst can be adjusted to get a shorter or longer gel time.

2.2.3 Butanox M-50

It is a general purpose methyl ethyl ketone per oxide (MEKP) for the curing of unsaturated polyester resins in the presence of cobalt accelerator at room and elevated temperatures. The curing system Butanox M-50 catalyst is particularly suitable for the curing of gel coat resins, laminating resins and castings.

2.2.4 Mat fiberglass

It is most basic and widelyused type of fiberglass. The roll is a whole bunch of small fibers thrown together on a binder. There is no specific direction to the fibers, which makes them pretty universally strong and light. It is strong, light weight and used for many products. It is also much cheaper and less brittle material. Mat fiberglass is used in construction of boats, automobiles, aircraft, septic tanks, roofing, pipes etc.

2.2.5 Woven roving

This is a weave, where the long fibers are weaved together like a cloth. They are extremely thick and durable but are also heavier than mat fiber glass materials. They are not used as much because they often print their pattern through gelcoat. Woven Glass fiber cloths are very common for marine and composite construction and repair. Light weight cloths tend to provide a smooth finish and are excellent for producing a water proofing layer over wood surfaces when combined with the appropriate resin. Heavier cloths will provide greater strength and overall rigidity.

2.3 IMPORTANCE OF STRENGTHENING

Necessity of strengthening of RC deep beams with large openings is majorly depends on the type of construction of opening in the RC deep beam, whether pre-planned or post-planned. Strengthening of RC deep beams with openings is not necessary if the openingis designed as built or pre-planned, since the location and sizes of the opening were specified and sufficient reinforcement is provided during design phase and construction of the deep beam. However, for post-planned opening in RC deep beam, strengthening of RC deep beam is required to ensure sufficient shear capacity to prevent structural failure. For post-planned opening case, the opening has to be constructed in an existing RC deep beam by hand tool drilling technique. There might be some difficulties during the process of creating service utility pipes and ducts. Therefore, it is necessary for the deep beam's opening to be strengthened externally by laminating fiber glass reinforced polymer.

Limited studies have been reported in the literature on the behavior and strength of deep beams and deep beams with openings. Deep beam is defined as the beam in which a significant amount of the load is transferred to the supports by a compression thrust joining the load and the reaction. According to the Building Code Requirements for Structural Concrete (ACI 318-02) [1] published by American Concrete Institute, a beam is classified as a deep beam for flexural if the beam's clear span/ beam's effective depth ratio is less than 1.25 for simply supported beams and 2.5 for continuous beams whereas deep beams is defined for shear if the beam's clear span/ beam's effective depth ratio is less than 4 for simply supported beams loaded on one face and supported on the opposite face so that compression struts can develop between loads and supports.

Web openings are generally introduced to accommodate building services such as air-conditioning ducts and electrical cables to save space, as these would otherwise be located below or within the deep beam. An opening produces geometric discontinuity within the beam as well as internal reinforcement and affects the nonlinear stress distribution over the depth of the beam. The creation of web openings decreases the ultimate strength capacity of a deep beam that can be attributed to the reduction of concrete mass acting in compression, and the opening acting as a stress raiser for shear crack propagation. This is particularly apparent when the opening is located along the critical load path of a deep beam.

2.4 STRENGTH AND BEHAVIOR OF REINFORCED CONCRETE SOLID DEEP BEAM

Many researchers have analyzed the behavior of reinforced concrete deep beams either in high or normal strength concrete with and without web openings. However, most of the researches have been carried out primarily focused on simply supported solid deep beams with various loading conditions.

Based on an experimental study on "Behavior of Concrete Deep Beams with High Strengthening Reinforcement", by Swami P.S [3] a total of eighteen deep beams are casted. After 28 days, curing for test specimens has been done and to assure the material quality and strength the reinforcement bars and concrete cubes are tested. From the experiment, it was concluded that the increase in shear span was resulted decrease in of initial cracking load and failure load. After casting curing has been done for next 28 days. The concrete cubes and steel bars are tested to assure material quality and stipulated strength. It was concluded from the test results, due to increase in shear span, there was decrease in initial cracking load and failure load. In this case due to use of high strength reinforcement the shear strength of deep beam is found 6 times greater than design loads.

An experimental research worked on "Investigation of Experimental and Analytical Shear Strength of Reinforced Concrete Deep Beams" was carried out by Abolfazl Arabzadeh [4] to investigate the shear strength of reinforced concrete deep beam. A total of sixteen reinforced concrete deep beams with compressive strength in range of59 MPa $\leq$ f'c $\leq$65 MPa were tested under two-point top loading. The shear span-to-effective depth ratio a/d was 1.10 and all samples were simply supported. The general behavior of tested beams was investigated. Observations were made on mid-span and loading point deflections, cracks form, failure modes and shear strengths. It was conclude from the result:

i. Amount and arrangement of shear reinforcement are effective on maximum strength of deep beams and the closely spaced shear reinforcement in the middle region of shear span have higher efficiency on strengthening of deep beams.
ii. The horizontal shear reinforcement can increase the shear strength of reinforced concrete deep beams as well as the vertical reinforcement. The efficiency of horizontal reinforcing decreases due to increasing of shear span-to-depth ratio.

2.5 STRENGTH AND BEHAVIOR OF REINFORCED CONCRETE DEEP BEAM WITH OPENINGS

Compared to solid deep beams, there has been little work done with reinforced concrete deep beams with web openings. Typically, large openings through structural members are necessary for building services such as mechanical and electrical conduits, or even for means of passageways. Besides, web openings in deep beams may be desired for windows and doors, or for passage of utility lines and ventilation ducts.

Reduction in building story height may occur to allow openings in deep beams for the transition of these utilities. This research mainly focuses on the ultimate strength and behavior of deep beams having opening holes.

According to a research work by Saeed Ahmed [5] "Flexural Behavior of Reinforced Concrete Beams with Opening", twenty seven beam specimens were casted. The beam specimen without opening was taken as a control beam and the remaining specimens were constructed with openings at different locations. These specimens were tested under four-point loading arrangement. The effect of size of holes at different locations was observed in terms of maximum failure load, maximum deflection and failure mode. In this research, it was concluded that the maximum load carrying capacity of the RC beams at shear zone with holes was maximum reduction but minimum reduction at flexure zone was noticed. According to this research, rectangular holes showed an increase in the maximum load reduction as compared to square holes by 4%, while the circular holes reduced the maximum load reduction than square opening by 8%.

An experimental study on "Behavior of Reinforced Concrete Beams with Openings in the Shear Zone", by S.C Chin [6] was conducted to study the behavior of RC deep beams with openings. One opening for each of two shear spans, was constructed near the supports at the middle of the shear span of the beam. Test parameters for this study were the size and shape of the opening holes. The shapes of the openings were circular and square. The sizes of the openings taken for this research were Φ150mm, Φ200mm and Φ250mm for circular and 150 x150mm, 200 x 200mm and 250 x 250mm for square openings. The cross section of the beam samples were 100mm x 500mm and the length of 1200mm. The beam samples were tested under four-point loading until failure. From the results obtained, the application of circular opening with the diameter could reduce the load carrying capacity of the beam to a range of 30-35% as compared to the capacity of solid beam. The inclusion of square openings of the considered dimension could a significant loss of load carrying capacity of the beam, about 40-80% as compared to the beam capacity of beam without openings. From this study it was concluded that, increasing the opening size, the more significant was the decrease of beam capacity with more sever and excessive diagonal shear cracks. According to the shape, circular opening is the most preferable option to be provided in RC beams as square openings produces sharp corners which is vulnerable to high stress concentration that causes to initial cracking in beam.

2.6 EFFECTS OF OPENINGS

2.6.1 Shape of opening

A study worked on “Effect of openings in deep beams with varying span to depth ratios using strut and tie model method”, by Nishitha Nair and Kavitha [7]was conducted to determine the effect of openings in deep beams using strut and tie model approach. A total of seven deep beams which are designed as per ACI 318, with different locations of opening as per strut and tie formation. This study was conducted to determine the effect of increasing length to depth ratio keeping length to depth fixed. From the results of this study it was concluded that deep beams with openings showed a decrease in maximum load carrying capacity than beams without openings. Also deep beams with rectangular openings showed that a decrease in maximum load carrying capacity than circular openings. As length to depth ratio increased, the load carrying capacity of the beam decreased.

2.6.2 Size of opening

A research on “Effect of Openings with various Size and Location on RC Deep Beam”, by Siow Sin Yang [8] was about analysis of the behavior of the reinforced concrete deep beam with different sizes of opening and different location of the opening by using ANSYS. The opening on RC deep beam was provided for the passage of pipes and electrical cables. Before the opening hole is provided, it is necessary to know the required size of the opening and the location where it is provided to avoid failures of the structure. In this research, a total of 7 models; one beam without opening, three beams with various sizes of opening and in the remaining three beams, the openings were provided in various locations. The three point loading was used for the analysis. The deflection and the crack pattern obtained from the analysis were used for discussion. According to the results of this study, the deflection of the RC deep beam model was increase by 31.2% when the opening size increase by 60%. In case of different location of opening, as the location of opening changed from 350mm to middle of the RC deep beam, the deflection of the RC deep beam was increased by 31.8%. In conclusion, the most suitable location of the opening on the RC deep beam is far away from the loading point.

Based on similar researches, performed by Waleed A. Jasim [9] an experimental study on “Effect of Size and Location of Square Web Openings on the Entire Behavior of Reinforced Concrete Deep Beams”, five simply supported reinforced concrete deep beam specimens with two large holes were provided in shear zones. The experimental study includes one specimen without opening which was taken as a control beam and the remaining four beams were provided with square openings placed at the middle and at the interior edge of the shear span. These two openings were provided symmetrically relative to the mid span section of the deep beam. Parameters to be studied were the size and location of openings in shear span. The dimensions for the square openings were 200x200mm and 230x230mm. All deep beam specimens were rectangular cross-section of dimensions of 150mm x 500mm and a total length of 1500mm. The effective span for the specimens was considered to be 1300mm with two shear spans each of 550mm, accordingly, the shear span to overall depth ratio was used to be 1.1. The ratio of the opening side dimension to the beam depth was considered to be 40% and 46% for beams with square opening of 200x200mm and 230x230mm dimensions, respectively. In this study, both square openings were considered as large opening because the dimensions of the openings were sufficient to cause reduction in capacity of the beam. From the test results and the numerical analysis, when compared to the control beam specimen, as the opening size increased from 200×200 mm to 230×230 mm the decrease in the load carrying capacity was increased from 58% to 66%, respectively. Also, this increasing caused to considerable decreasing in the overall stiffness of the beam specimens.

2.6.3 Location of opening

A research studied on “Effect of Opening Shape and Location on the Structural Strength of RC Deep Beams with Openings”, by Haider M. Alsaeq [10] used test parameters, opening shape and location to study their effect on the load carrying capacity of reinforced concrete deep beam with openings, by remaining the opening size unchanged. The software ANSYS 12.1 was carried out to handle the nonlinear finite element analysis. The maximum capacity of reinforced concrete deep beam with opening obtained by the software shows almost same results with the experimental investigation, but a difference of no more than 20%. From the research it was concluded that, placing of the opening in different location has much more effect on the structural capacity of the beam than the shape of the opening. It was noticed that locating the openings at the upper corners of the deep beam may increase the strength by two times the original strength, and the use of a rectangular smaller opening having the longer sides in the horizontal direction can save up to 40% of structural strength of the deep beam.

2.7 STRENGTHENING OF DEEP BEAM

2.7.1 Glass fiber reinforced polymer (GFRP)

Glass fiber is a fiber reinforced polymer which is made up of plastics reinforced by glass fibers, commonly woven into a mat. The plastic may be a thermosetting plastic- most often epoxy, polyester- or vinyl ester or a thermoplastic. Glass fiberis made of different types of glasses depending upon its use. It is a strong and light material and is used for various products. It is less brittle, and its raw materials are much cheaper. Its bulk strength and weight are also better than many metals, and it can be easily molded into complex shapes. Applications of fiberglass include aircraft bodies, boats, automobile bodies, bath tubs and enclosures, hot tubs, septic tanks, water tanks, roofing, pipes, cladding, casts, surfboards and external door skins.

An experimental study on “Behavior of High Performance Continuous RC Deep Beams with Openings and its Strengthening”, by Mohamed M. Rashwan [11]was conducted including twelve reinforced concrete two-span continuous deep beams. Test specimens were constructed and tested to failure under the effect of two point loads one was placed at each span. All specimens were constructed using high performance concrete. The openings of all specimens were provided with glass fiber to improve its strength. The glass fiber was provided on all specimens around the openings and extended to a distance of 7.5cm all of its surroundings of the opening within the width of the specimens. Based on the results obtained from the experiments, the following conclusions were drawn:

- The provision of web openings inside and outside of the shear span had significant effects on the strength of the beam. Presence of web openings within the shear spans could be resulted in a high reduction in the shear capacity of the beams. In all beams, the first diagonal shear cracks were started at the top and bottom corners of web openings and extended to the load points at different load levels.

- The provision of glass fiber reinforced polymer around the openings at shear zone had large effect but not large effect when the openings were provided in flexure zone.

"Experimental Analysis of Deep beam Strengthened by Glass Fiber Reinforced Polymer Plate" by Sayali Anil Kedge and M.V.Nagendra [12] was performed on an experimental investigation on the flexural and shear behavior of RC deep beams strengthened using continuous glass fiber reinforced polymer plate (GFRP) sheets. In this study, reinforced concrete deep beam specimens were laminated externally by using glass fiber reinforced polymer plate sheets and tested to failure under two point static loading system. Test specimens were constructed and tested in two groups. In first group, three beam specimens, out of which is one is a reference beam were strengthened using continuous glass fiber reinforced polymer sheets in flexure zone. In the second group, three beam specimens one of them was a reference beam were strengthened with same material in shear zone. From the test results, with the application of large amount of load, the first diagonal shear crack appears at soffit of the specimen. The maximum load carrying capacity of strengthened deep beam was higher than the reference deep beam. Further load was increased by strengthening the beam at the bottom face as well as on the two faces of the deep beam. The ultimate load carrying capacity of strengthen this deep beam was higher than the controlled beam and higher than the strengthened deep beam on the bottom face.

2.7.2 Carbon Fiber Reinforced Polymer (CFRP)

Based on an experimental study on "Shear Resistance of Reinforced Concrete Deep Beams with Opening Strengthened by CFRP Strips" by Ban Sahib Abduljalil [13] the behavior and performance of reinforced concrete deep beams with opening strengthened with externally bonded CFRP strips failed in shear was presented. In this study, a total of eight specimens were casted and tested. The parameters considered in the experimental investigation were the effect of fiber orientation (90º or 45º CFRP strips with respect to beam longitudinal axis), the effect of using longitudinal CFRP strips with vertical CFRP strips and effect of anchoring the vertical CFRP strips. Test results were according to mid span deflection, strain in CFRP and maximum crack width of beams. From the results it was concluded that externally attached CFRP strips can significantly increase the maximum shear capacity and limit the shear crack width and increase the stiffness of the deep beams with opening.

An experimental study performed on "Experimental Study of Strengthening of RC Deep Beam with Web Opening", by Punnoose and Hameed [14] was conducted on strengthening of reinforced concrete deep beams with circular opening using carbon fiber reinforced polymer.

In this study, a total of eight deep beam specimens, with one opening, two opening and specimen without opening were constructed. All specimens were tested under point loading of 50Ton. All the specimens tested under point loading failed in perfect diagonal compression shear. In all the beams cracks were appeared as flexural cracks, but cracks were not observed up to 45% of the maximum load. At each increment of load, deflections formed at the mid span and at the two ends were recorded. During testing of beam specimens, the load at which first crack was recorded and the crack propagations were carefully marked. In all specimens first cracks were observed after 40% of the maximum load and most all of them were flexural cracks. By further loading of the specimen shear cracks were observed and the diagonal shear cracks get widened at the maximum load. In all the cases a sudden shear failure was observed at the failure load. All existing cracks were observed between 40 to 70% of ultimate load.

2.8 CRITICAL OBSERVATIONS

The following critical observations are made from the existing literature in the area of reinforced concrete deep beams with openings and reinforced concrete deep beams with openings strengthened by fiber reinforced polymer (FRP).

- ✓ Most of the reported studies are limited to deep beams with openings.
- ✓ Limited work is done in deep beams with openings strengthened by CFRP.
- ✓ Very few studies reported in deep beams with openings strengthened by GFRP.

CHAPTER 3 DESIGN OF DEEP BEAMS

3.1 INTRODUCTION

This chapter deals with the design criteria of deep beams. The following are the criterion to design a deep beam as per American Concrete Institute ACI. [1]

3.1.1 Definition

As per clause 318 [1]: A beam shall be deemed to be a deep when the shear span to depth ratio is less than 4 for concentrated load.

3.1.2 Design criteria for flexure

- Nominal Resisting moment, $M_n = A_s f_y$…………………….................................. **(3.1)**

- The reinforcement area "A_s" for flexure is

$$A_s = \frac{M_u}{\varphi f_y jd} \geq 3\sqrt{f'_c}\,\frac{bd}{f_y} \qquad (3.2)$$

Moment capacity for simply supported beams can be given as:

$$M_n = A_s f_y (jd) \qquad (3.3)$$

3.1.3 Detailing of reinforcements

- All positive bars should extend through the span without curtailment beyond the supports and preferably bent upwards at the ends to obtain adequate embedment and anchorage.
- Half the negative bars over the support should extend over full length of the adjacent spans. The other half can be stopped at a distance of 0.4L or 0.4h, where L and h are the length and height of the beam, whichever is smaller, from the edge of the support.
- Flexural reinforcements are uniformly placed using relatively small size bars over a vertical distance of (0.25h-0.05L) for positive bending moment, where the vertical distance is measured from bottom extreme face of the cross section.

Table 3-1 Design criteria for flexure in deep beam [1]

TYPE	SIMPLY SUPPORTED BEAM	CONTINUOUS BEAM
Moment Capacity	$M_n = A_s f_y(jd)$	$M_n = A_s f_y(jd)$
Positive Reinforcement	$A_s^+ = \frac{M_u^+}{\left(\varphi f_y(jd)\right)}$	$A_s^+ = \frac{M_u^+}{\left(\varphi f_y(jd)\right)}$
Negative Reinforcement	-	$A_s^- = \frac{M_u}{\left(\varphi f_y(jd)\right)}$
A_s Minimum	$A_{s-min} = \frac{\sqrt{f'_c}}{4f_y} b_w d$	$A_{s-min} = \frac{1.4}{f_y} b_w d$
Lever Arm	$Jd = 0.2(L+2h) \rightarrow 1 \le \frac{L}{h} < 2$ $Jd = 0.6L \rightarrow \frac{L}{h} < 1$	$Jd = 0.2(L+1.5h) \rightarrow 1 \le \frac{L}{h} \le 2.5$ $Jd = 0.5L \rightarrow \frac{L}{h} < 1$
Positive Reinforcement distribution	Vertical spacing $Y= 0.25h-0.05L\le 0.20h$	Vertical spacing $Y= 0.25h-0.05L\le 0.20h$
Negative Reinforcement distribution	-	$A_{s1}^- = 0.5\left(\frac{L}{h} - 1\right) A_s$ $A_s^- = A_s - A_{s1}$

3.1.4 Shear design of deep beam

Basic design equation for deep beam is:

$$\varphi V_n \ge V_u \quad \text{……………………………………………………………………..} \quad \textbf{(3.4)}$$

Where:

- V_n = Nominal shear strength
- φV_n = Design shear strength
- φ = Strength reduction factor (0.85)
- V_u = Ultimate shear force, factored shear force

As a shear design of ordinary beam, the shear force is resisted by the concrete component and by the shear reinforcement component, as follows:

$$\boldsymbol{V_n = V_c + V_s} \quad \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots \quad \textbf{(3.5)}$$

Where:

- V_n= Nominal shear strength
- V_c = Concrete shear strength without shear reinforcement
- V_s = Shear reinforcement (stirrups) shear strength

3.1.5 Design procedure for shear design of deep beam

➢ Determine the critical section to calculate the ultimate shear force V_u.

Table 3-2Critical section for deep beam

UNIFORM LOAD	CONCENTRATED LOAD
$x = 0.15(L_n)$	$x = 0.50(a)$

➢ Check the ultimate shear force; enlarge the section if the condition is not achieved.

$$V_u \leq \Phi \, x \frac{2}{3}\sqrt{f'_c} b_w \, d \quad \text{for} \frac{L_n}{d} < 2.0 \dots\dots\dots\dots \quad \textbf{(3.6)}$$

$$V_u \leq \Phi \left\{\frac{1}{18}\left(10 + \frac{L_n}{d}\right)\sqrt{f'_c} b_w \, d\right\} \quad \text{for } 2.0 \leq \frac{L_n}{d} \leq 5.0 \quad \dots\dots\dots\dots \quad \textbf{(3.7)}$$

Calculate the concrete shear strength V_c:

$$V_c = \left[3.5 - 2.5\frac{M_u}{V_u d}\right]\left(\frac{1}{7}\right)\left[\sqrt{f'_c} + 120\,\rho_w \frac{V_u\, d}{M_u}\right] b_w \quad \dots\dots\dots\dots \quad \textbf{(3.8)}$$

$$1.0 \leq \left[3.5 - \frac{2.5 \;\; M_u}{V_u d}\right] \leq 2.50 \quad \dots\dots\dots\dots \quad \textbf{(3.9)}$$

Where

V_c = Concrete shear strength (N)

M_u = Ultimate flexure moment (Nmm)

V_u = Ultimate shear force (N)

f'_c = Concrete cylinder strength (MPa)

d = Effective depth

b_w = Width of beam web

ρ_w = Longitudinal reinforcement ratio

Or, the concrete shear strength can be determined as:

$$V_c = \frac{1}{6}\sqrt{f'_c}b_w\, d \quad \text{(3.10)}$$

The maximum limit of concrete shear strength is:

$$V_{c-max} = \frac{1}{2}\sqrt{f'_c}b_w\, d \quad \text{(3.11)}$$

- If $V_u < 0.5\varphi V_c$, then no shear reinforcements needed, but for practical reason provide minimum shear reinforcement area.

  $A_{vh-min} = 0.0025(b_w S_h)$

  $A_{v-min} = 0.0015(b_w S_v)$

A_{v-min} = Minimum area of vertical stirrups

A_{vh-min} = Minimum area of horizontal stirrups

b_w = width of beam

S_v= Spacing of vertical stirrups

S_h= Spacing of horizontal stirrups

If $V_u > \varphi V_c$, then provide the shear reinforcement

- Calculate the ultimate shear force carried by the stirrups V_s.

$$V_s = \left\{\left[\frac{A_v}{S_v}\frac{1+\left[\frac{L_n}{d}\right]}{12}\right] + \left[\frac{A_{vh}}{S_h}\frac{11-\left[\frac{L_n}{d}\right]}{12}\right]\right\} f_y\, d \quad \text{(3.12)}$$

$$V_s \geq \frac{V_u}{\varphi} - V_c \quad \text{(3.13)}$$

Where L_n is effective length of beam.

- Check the spacing of shear reinforcements S_v and S_h.

Table 3-3 Spacing for shear reinforcements in deep beam

VERTICAL STIRRUPS	HORIZONTAL STIRRUPS
$S_v \le \frac{d}{5}$	$S_h \le \frac{d}{3}$
$S_v \le 500mm$	$S_h \le 500mm$

.

- If necessary check the chosen shear reinforcements for the basic design equation for the shear design.

  $V_n = V_c + V_s$

3.2 MINIMUM THICKNESS

The minimum thickness of deep beams should be based on two considerations.

First, it should be thick enough to prevent lateral buckling with respect to its span. Second, the thickness should be such that the concrete itself should be able to carry a good amount of the shear force that acts in the beam without the assistance of any steel.

CHAPTER 4 EXPERIMENTAL STUDY

4.1 INTRODUCTION

This chapter presents the details of the experimental setup such as materials properties, experimental works and laboratory testing that have been undertaken to determine the behavior of reinforced concrete deep beams with and without inclusion of openings subjected to variations in opening size, shape, and location. Slump test and compressive strength test were conducted to determine the properties of fresh concrete and hardened concrete. All the experimental procedures are explained in details with relevant information for further understanding.

4.2 CASTING OF BEAMS

4.2.1 Beam dimensions

The beam dimensions were finalized as follows:

Length (L) = 1050mm

Width (b_w) = 100mm

Depth (D) = 500mm

Effective span (L_n) = 870mm

Effective depth (d) = 471mm

It has been tested after 28 days with point loading.

4.2.2 Casting of specimen

The mix design proportion used in this study is summarized in table 4-1. Three cubes are casted and tested after 28 days to determine the compressive strength of concrete for 28 days.

Table 4-1 Mix design

S.No.	Particulars	Quantity (Kg/m^3)
1	Mass of cement	387.55
2	Mass of fine aggregate	734.07
3	Mass of coarse aggregate	942.82
4	Mass of water	180.66

4.2.3 Materials for casting

4.2.3.1 Cement

Dangote Ordinary Portland Cement (OPC) is used for the experiment. It is having a specific gravity of 3.15.

4.2.3.2 Fine aggregate

The fine aggregate passing through 4.75mm sieve and having the following properties are used:

- Silt content = 1.33%
- Unit weight = 1,332.20 kg/m^3
- Moisture content = 1.63%
- Specific gravity = 2.33
- Absorption capacity = 1.83%
- Fineness = 2.7

4.2.3.3 Coarse aggregate

- Unit weight = 1,425.20kg/m^3
- Moisture content = 1.52%
- Specific gravity = 2.51
- Absorption capacity = 1.54%

4.2.3.4 Water

Ordinary tap water is used for concrete mixing in all the mix.

4.3 MATERIAL PROPERTIES

In this section, the materials that used in formwork fabrication and completion of RC deep beam were discussed. Concrete and reinforcement steel bar are the most important materials in production of the RC deep beams. Furthermore, involvements of GFRP, gelcoat white, general purpose resin and the catalyst are essential to strengthen the RC deep beam with large circular and square openings.

4.3.1 Concrete

A total of 0.47 m^3 concrete used in the experimental study. The grade C-30 concrete was prepared in Addis Ababa Institute of Technology Laboratory. Ordinary Portland cement (OPC) was used as the raw material of concrete in order to produce a normal mix concrete with a 28 days target compressive strength of 38 N/mm^2 without any addition of additives. The concrete covers with 15 mm in thickness were casted manually. The purpose of concrete cover is to avoid the reinforcement steel bar in contact with the formworks as well as reduction of beam serviceability. All the RC deep beams were casted with the same batch of concrete, in order to standardize the quality and strength of the RC deep beams.

Figure 4-1Compaction of concrete with a needle vibrator

4.3.2 Steel

The longitudinal steel reinforcements and shear reinforcements were deformed steel bars. The tensile steel bar used is deformed steel bar Φ12 in order to provide sufficient tensile reinforcement whereas compression steel bar of deformed steel bar Φ10 is used to provide compression reinforcement and 8mm diameter bars are used as stirrups. The reinforcement steel bars used are shown in Figure 4.2.

Table 4-2 Details of reinforcement in deep beam

S.No.	Type of reinforcement	Details of reinforcement
1	Main tension reinforcement	2Φ12
2	Main compression reinforcement	2Φ10
3	Vertical shear reinforcement	10Φ8 at 90mm c/c

Figure 4-2Fixing for tension, compression and shear reinforcements

Figure 4-3Testing for steel bars for tensile strength

Table 4-3Tensile strength and elongation of steel bars

Specimen No	Diameter		Yield Load (KN)	Yield Strength (N/mm^2)	Failure Load (KN)	Tensile Strength (N/mm^2)	Elongation (%)
	D1(mm)	D2(mm)					
ϕ8-1	7.85	8.39	27.6	532.98	33.2	641.56	15
ϕ8-2	7.82	8.15	28.7	573.83	33.2	662.94	14
ϕ8-3	7.85	8.23	28.9	569.24	34.7	683.47	16.5
ϕ10-1	10.30	10.95	47.8	539.62	56.7	639.52	16
ϕ10-2	10.35	11.02	48.0	535.81	56.1	625.63	15
ϕ10-3	10.29	11.12	48.0	533.81	56.5	627.78	16
ϕ12-1	12.18	12.86	69.8	566.97	79.2	643.33	17
ϕ12-2	12.22	12.92	68.9	554.33	78.5	632.60	17
ϕ12-3	12.16	12.84	70.4	573.67	79.7	649.44	15

4.3.3 Form work

Form work is the term given to either temporary or permanent molds in to which concrete or similar materials are poured. In this study nine plywood molds of the same dimensions were prepared for casting the deep beam samples to be casted. PVC pipes of 110 and 160mm diameter and plywood boxes of 110x110mm and 160x160mm were used to create circular and square openings respectively. In order to easy de-molding after casting, the molds were properly cleaned and greased. The deep beams were cast in the form work of same dimensions of 1050mm, 100mm and 500mm.

4.3.4 Glass fiber

Fiberglass (or glass fiber) (also called glass-reinforced plastic, GRP, glass-fiber reinforced plastic, or GFRP) is a fiber reinforced polymer made of a plastic matrix reinforced by fine fibers of glass. Fiberglass is a lightweight and extremely strong material. The glass fibers are divided into three classes: E-glass, S-glass and C-glass. The E-glass is designated for electrical use and the S-glass for high strength. The C-glass is for high corrosion resistance, and it is uncommon for civil engineering application. Of the three fibers, the E-glass is the most common reinforcement material used in civil structures.

Table 4-4Properties of Glass fiber [5]

Typical properties	E-Glass	S-Glass
Density(g/cm^3)	2.60	2.50
Young's Modules (GPa)	72	87
Tensile Strength (GPa)	1.72	2.53
Tensile Elongation (%)	2.4	2.9

4.4 CUBE CASTING

A total of 27 cubes of size 150x150x150 mm, three cubes for each deep beam were casted and tested to determine the 28 days compressive strength of the deep beam under compression testing machine.

4.5 MIXING, COMPACTING AND CURING OF CONCRETE

Mixing of concrete is done thoroughly with the help of machine mixer so that a uniform quality of concrete is obtained. Compaction is done with the help of needle vibrator in all the specimens and care is taken to avoid displacement of the reinforcement inside the form work. Then the surface of the concrete is leveled and smoothened by metal trowel and wooden float. Curing is done to prevent the loss of water which is essential for the process of hydration and hence hardening. It also prevents the exposure of concrete to a hot atmosphere and to drying winds which may lead to quick drying out of moisture in the concrete and thereby subject it to contraction stresses at a stage when the concrete would not be strong enough to resist them. Here curing is done by spraying water over the surface for a period of 14 days.

4.6 EXTERNAL STRENGTHENING OF BEAMS

In this research, the shear strengthening of reinforced deep beams was performed using mat fiberglass and woven roving. The specimens were strengthened with GFRP of thickness of 3mm.

Following materials were used for fabrication of glass fiber reinforced polymer:

1. Gelcoat
2. General purpose resin
3. Methyl ethyl ketone per oxide or Butanox M-50 as a catalyst
4. Mat fiberglass
5. Woven roving

Before the application of the gelcoat white, the surface of the concrete was roughened using a hammer and chisel and cleaned to remove all dirt and debris to insure a good bond between the gelcoat and the concrete surface of the reinforced deep beam. After the application of gelcoat the resin is mixed with Butanox M-50 which is a catalyst to increase the time of curing in accordance with the manufacturer's instructions. The mixing was carried out in a plastic container by hand and applied on the surface of gelcoat painted beam. Then the fabrics are cut into the size of the beam and placed on the top of the resin coating and the resin is squeezed with the roller to eliminate air bubbles and to obtain a uniform thickness of the GFRP.

Figure 4-4Mat fiberglass

Figure 4-5Weaved fiber glass

Figure 4-6Strengthened beams with GFRP

4.7 SPECIMEN DETAILS

In this experimental study, nine reinforced concrete deep beams were casted. Beams with rectangular cross section of h x b = 500 x 100mm with an overall length of 1050mmwere prepared. Two deformed Φ12 bars on the bottom and two deformed bars with 10mm in diameter at the top were provided. For the stirrups, 8mm diameter deformed bars with a spacing of 110mm were used. Circular openings of diameter 110 and 160mm and square openings of 110x110mm and 160x160mm were provided. The openings were provided at the middle of half of the deep beam and arranged symmetrically. A concrete cover of 15mm was provided. Concrete with 28-day compressive strength of 37.6MPa and steel bar with yield strength of 400MPa for main reinforcement and 300MPa for stirrups was used.

Table 4-5Detail of deep beam specimen

S.No.	Beam Notation	Identification of specimen
1	Control Beam without hole	CB
2	Beam with circular hole of diameter 110mm.	B1
3	Beam with circular hole of diameter 160mm.	B2
4	Beam with square hole of 110x110mm.	B3
5	Beam with square hole of 160x160mm.	B4
6	Beam with circular hole of diameter 110mm laminated with GFRP.	C1
7	Beam with circular hole of diameter 160mm laminated with GFRP.	C2
8	Beam with square hole of 110x110mm laminated with GFRP.	C3
9	Beam with square hole of 160x160mm laminated with GFRP.	C4

4.8 EXPERIMENTAL SET-UP

The specimens were simply supported at both ends and tested for center-point loading as shown in Figure 4-7. The experimental investigation on the reinforced concrete deep beams for this work was carried out in the Civil Engineering Laboratory at Addis Ababa University, Addis Ababa Institute of Technology. The testing procedure for all the specimen is same. The surface of the beam is accurately prepared and cleaned with sand paper to make the cracks clearly visible after testing. Preparations and calibrations to all instrumentations and devices were prepared before the start of testing. Each of the beam specimens were mounted as simply supported beam. One point loading arrangement is used for testing of beams.

The load was tightened to ensure that the beam was properly seated and then the load was applied in increment of 10kN. The load is transmitted through a load cell which is placed at the midpoint of the beam. The specimens placed over two supports leaving 90mm from each end of the beam. The dial gauge is used for recording the deflection of the beam and placed at the center of the beam. During the test, the first crack load was observed and the crack propagations were carefully marked. All the beams were loaded till failure.

Figure 4-7 Experimental setup

4.9 TESTING OF BEAMS

All the nine beams are tested one by one. Four beams were strengthened with GFRP, four un-strengthened beams with openings of circular and square shapes and one is taken as the control beam. All of beams are tested in the above arrangement. The dial gauge reading shows the deformation. The load at which the first visible crack is developed is recorded as cracking load. Then the load is applied till the ultimate failure of the beam. The deflections at the midpoint mentioned for the beams with and without GFRP are recorded with respect to increase of load.

4.9.1 Control beam (CB) without opening

CB is taken as a control beam in which no strengthening is done. A single point loading is applied on the beam and at each increment of the load, deflection values at L/2 are taken with the help of dial gauge. At the load of 120kN first crack was appeared. The control beam was failed in shear.

Figure 4-8Control beam specimen after testing

4.9.2 Specimen B1

Un-strengthened beam B1 is constructed with circular opening of 110mm diameter. The load applied on the beam specimen and the deflection at the mid span was recorded from the data logger. The first visible crack was appeared at 110kN and with the increase of the load values the crack propagated further. Specimen B1 failed completely in shear producing diagonal cracks.

Figure 4-9Specimen showing cracks

4.9.3 Specimen B2

Specimen B2 was a beam with the openings of 160mm diameter and was un-strengthened. From the experiment the first crack was observed at the load of 50kN and with the increasing of load values, the cracks became wider and wider. Specimen B2 was failed in diagonal shear mode of failure.

Figure 4-10Flexural and shear cracks of B2

4.9.4 Specimen B3

Specimen B3 is constructed with 110 x 110mm square openings. The first hairline cracks were appeared at 70kN. From the experiment, crushing of concrete at the supports was observed. The specimen was failed at 264.61kN in shear.

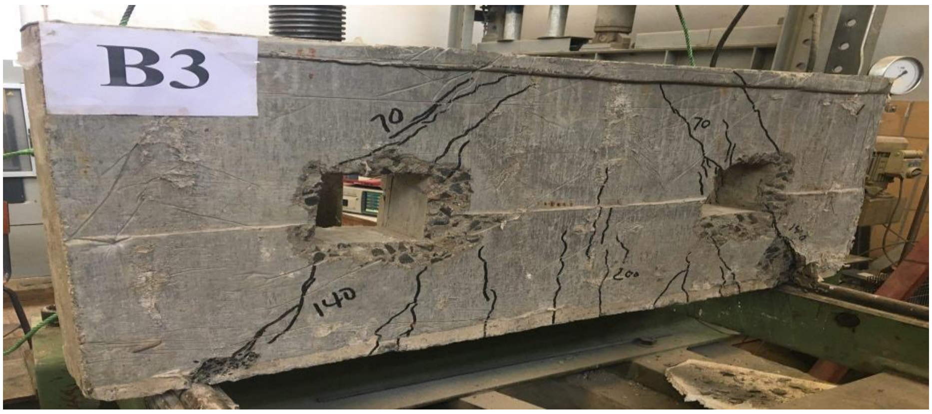

Figure 4-11 Shear and flexural cracks

4.9.5 Specimen B4

The cracking history of specimen B4 started with the appearance of diagonal cracks at the corners of its openings. As the specimen then exposed to additional loading, it experienced occurrence of additional diagonal cracks in other sections besides the opening zone. The failure of the investigated deep beam was characterized by diagonal cracking mode of failure, which was took place as the diagonal cracks at the opposite corners of the openings.

Figure 4-12Shear failure at the ultimate load

4.9.6 Specimen C1

Specimen C1 was strengthened with GFRP on both sides and failed by the rupture and de-bonding of GFRP sheets on the surface of the beam along with crushing of concrete at the supports as shown in the figure below.

Figure 4-13De-bonding of GFRP and crushing of concrete

4.9.7 Specimen C2

Specimen C2 has shown de-bonding of GFRP sheets along with crushing of concrete at the supports as shown in the figure below. Hairline cracks were observed at the inner side of the openings.

Figure 4-14De-bonding of GFRP and crushing of concrete at 340.14KN

Figure 4-15De-bonding of GFRP at the supports of the beam

4.9.8 Specimen C3

The modes of failure in specimen C3 were rupture and de-bonding of the GFRP sheets along with crushing of concrete at the supports and near the openings as shown in the figure below. Similar to C2, cracks were observed in the openings.

Figure 4-16De-bonding and rupture of GFRP sheet

Figure 4-17De-bonding and crushing of concrete at the supports

4.9.9 Specimen C4

As shown in the figure 4-18, de-bonding of the GFRP sheets from the surface of the deep beam and diagonal rupture were observed. Specimen C4 was failed at the load of 334.29kN.

Figure 4-18De-bonding and rupture of GFRP

CHAPTER 5 RESULTS AND DISCUSSIONS

5.1 INTRODUCTION

In this chapter, the results obtained from load test of all the beams are discussed in detail. Their behavior load-displacement data throughout the test has been recorded. Moreover, crack patterns and mode of failure of each beam are also described in this chapter. All the beams are tested for their ultimate strengths. All the beams are tested under static loading until failure occurs. Experimental load and deflection data were automatically recorded from the data logger. The crack patterns of un-strengthened beams and de-bonding and rupture of GFRP sheets of strengthened beams are shown in chapter four.

The control beam and other four reinforced concrete deep beams with circular and square openings B1, B2, B3 and B4 are not strengthened but the remaining four deep beams C1, C2, C3 and C4 are strengthened with GFRP.

5.2 MODES OF FAILURE OF EXPERIMENTAL DEEP BEAMS

Observed failure modefor deep beams without GFRP sheets is shear failure.

Failure modes for strengthened deep beams are:

- De-bonding of GFRP from the concrete surface.
- Rupture of GFRP sheets.

5.3 LOAD DEFLECTION AND CRACK OCCURS

In this section the deflection of each deep beam and the formation of cracks is analyzed. Also the load deflection behavior of the deep beam is compared between beams with and without GFRP sheets. At each increment of load, deflection values at the mid span are taken with the help of the dial gauge. Using the load and deflection data, load vs deflection curve is plotted.

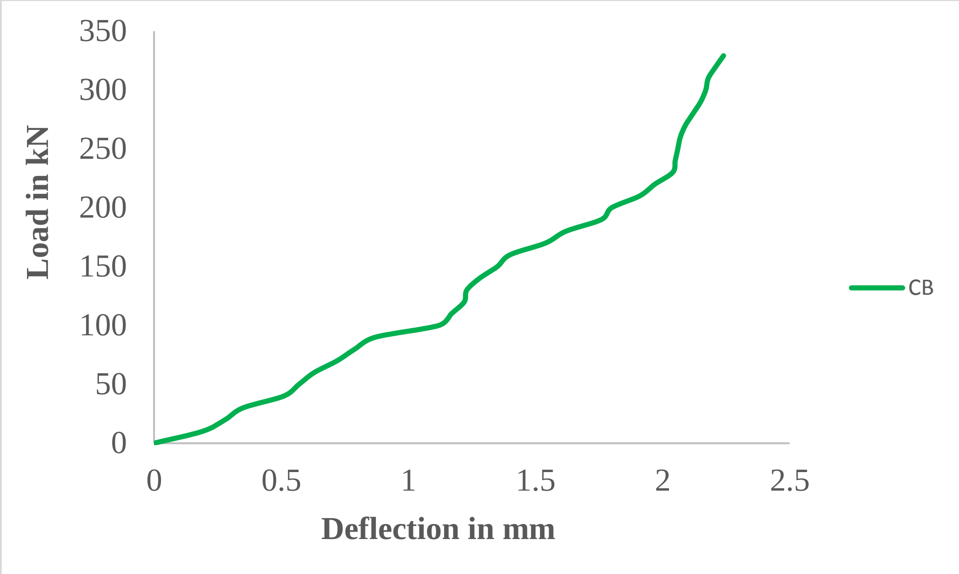

Figure 5-1Load Vs. deflection curve for control beam

For the control beam, the first visible crack was developed at the load of 120kN. New flexural cracks in the middle part of the member also occurred and propagated upward corresponding to the increment of the load. Shear cracks initiated afterward in the beam parallel to compression struts which connect from the inner of the support to the loading point. These diagonal cracks propagated upward to the loading point and downward to a location near support. With incremental loads, the width of diagonal shear cracks became wider and wider and extend into the loading point along with concrete crushing. From experimental observation, the control beam failed at the load of 329.13kN. The crack pattern of the control beam is shown in figure 4-8. The failure of the control beam was characterized by diagonal shear mode of failure.

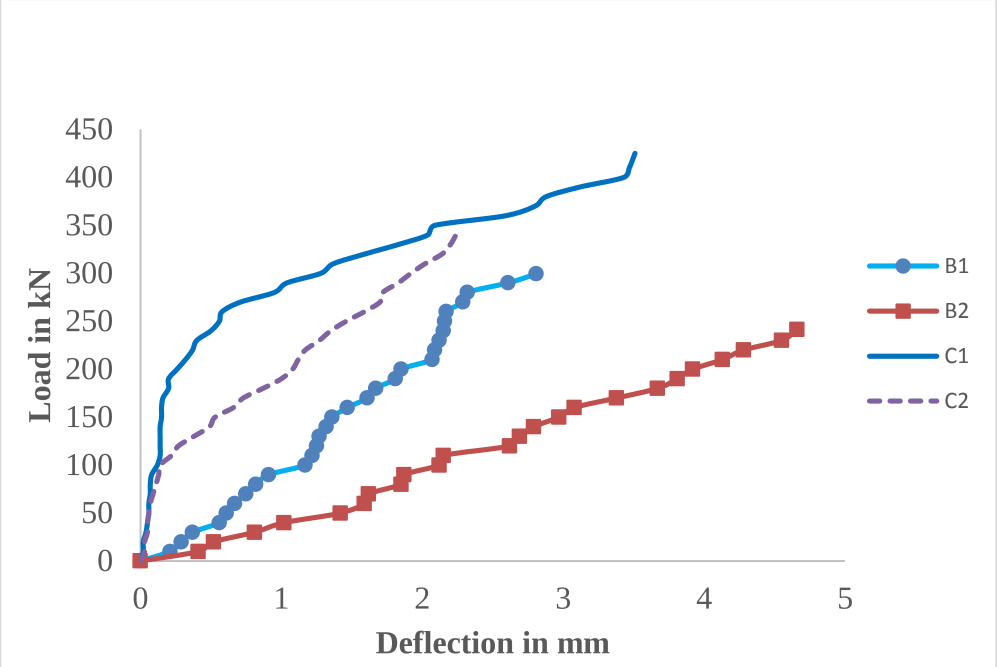

Figure 5-2Load-mid span deflection curve for B1, B2, C1 and C2

The ultimate load for beams B1, B2, C1 and C2 observed from the experiment was 299.37kN, 241.35kN, 425.13kN and 340.14kN with the corresponding deflection of 2.81mm, 4.66mm, 3.51mm and 2.24mm, respectively. The load carrying capacity of strengthened beams is increased by 42% as compared to un-strengthened beams.

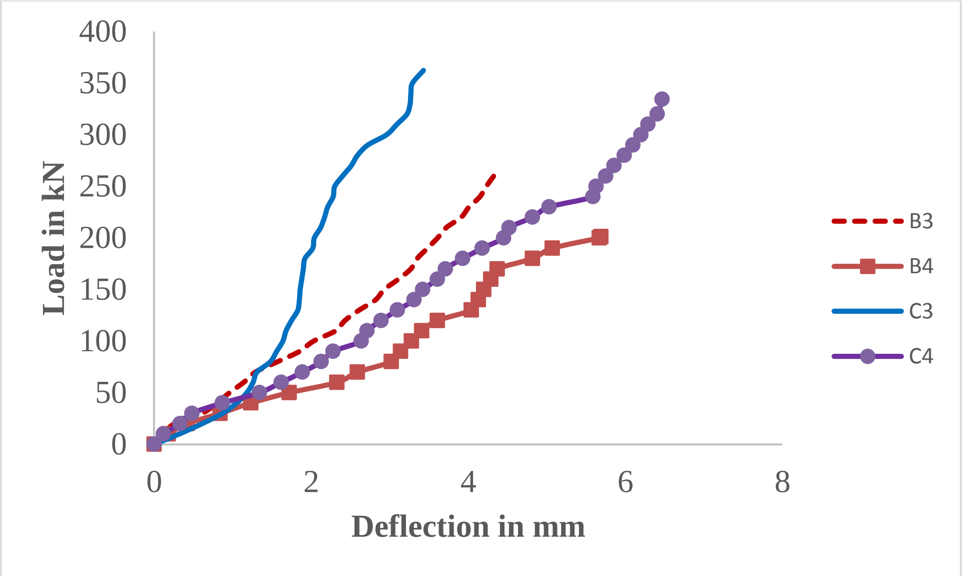

Figure 5-3Load-mid span deflection curve for B3, B4, C3 and C4

The ultimate load for beams B3, B4, C3 and C4 observed from the experiment was 264.61kN, 201.08kN, 362.41N and 334.29kN with the corresponding deflection of 4.37mm, 5.69mm, 3.43mm and 6.47mm, respectively. The load carrying capacity of strengthened beams is increased by 66% as compared to un-strengthened beams.

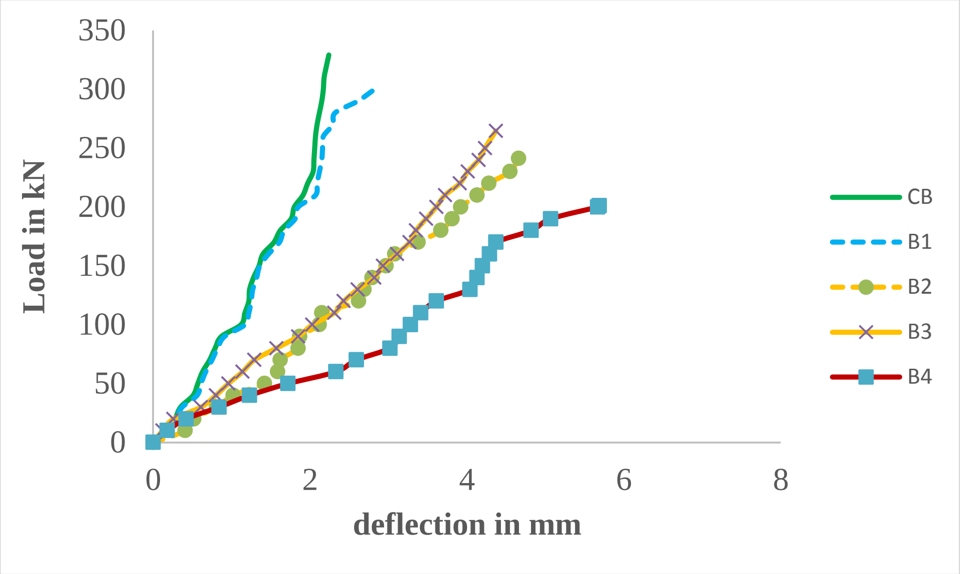

Figure 5-4 Load-mid span deflection curve B group specimens

From the experiment, as the size of both circular and square openings increased, the load carrying capacity of un-strengthened beams decreased from 9% - 27% and 20% - 39%, respectively, as compared to the control beam.

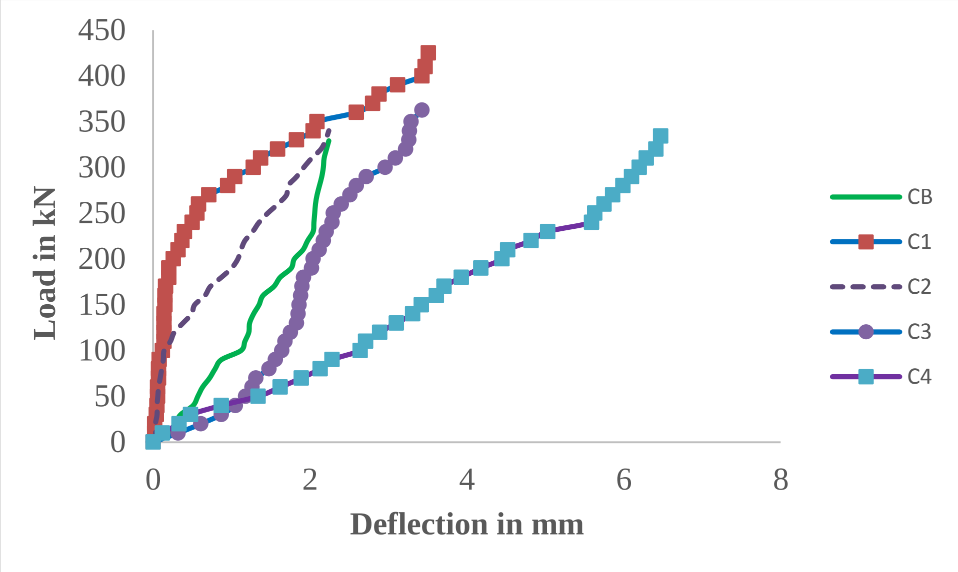

Figure 5-5 Load-mid span deflection curve C group specimens

In C group specimens, when the size of circular and square openings increased, the load carrying capacity is increased from 4% - 30% and 2% - 11%, respectively, as compared to the control beam. These beams are laminated strongly with GFRP sheets externally.

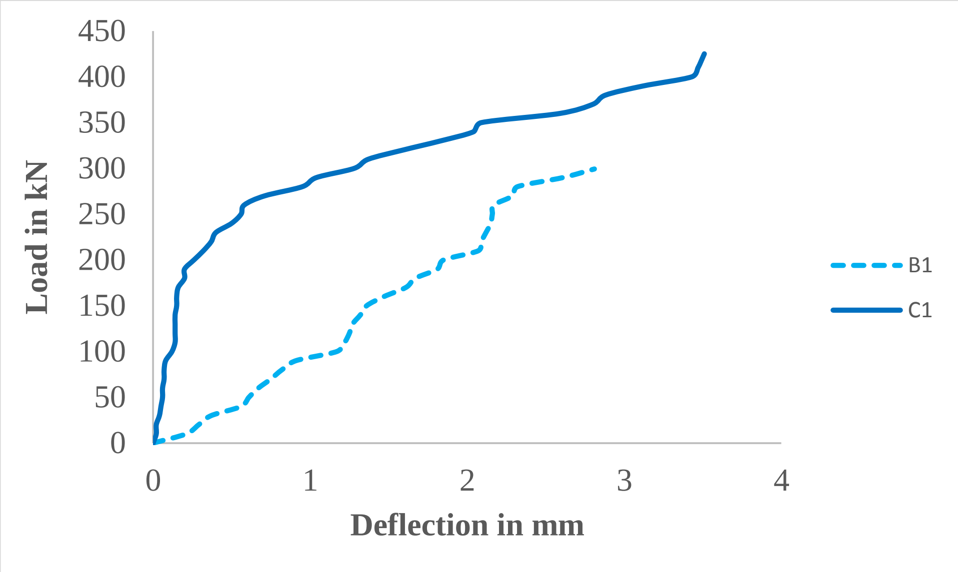

Figure 5-6Load-mid span deflection curve for B1 and C1

Due to the application of strong GFRP sheets on the surfaces of beam specimen, the load carrying capacity of the strengthened beam C1 was increased by 42% of the un-strengthened beam B1 and 30% of the control beam.

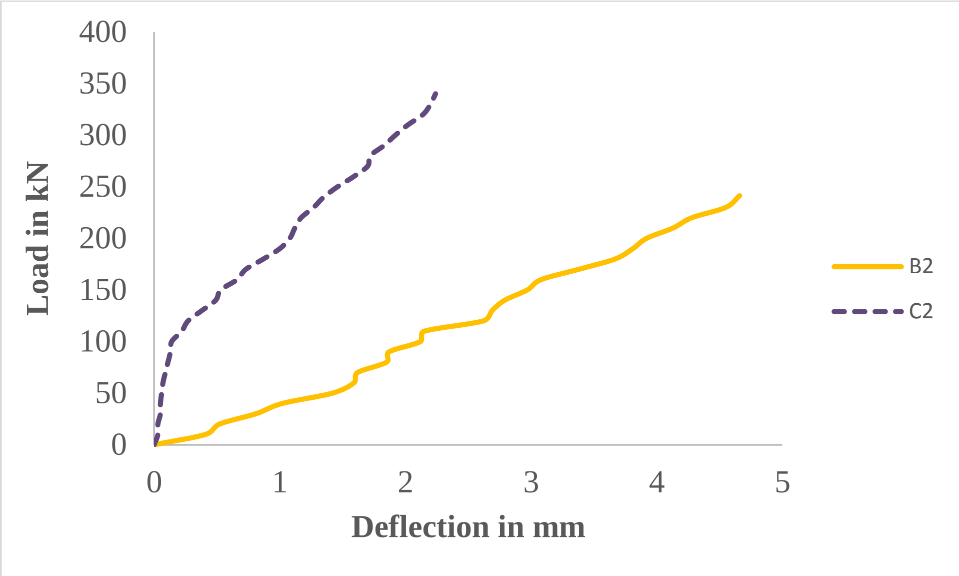

Figure 5-7Load-mid span deflection curve for B2 and C2

From the experimental results, the load carrying capacity of C2 is increased by 41% as compared to B2 and 4% from the control beam.

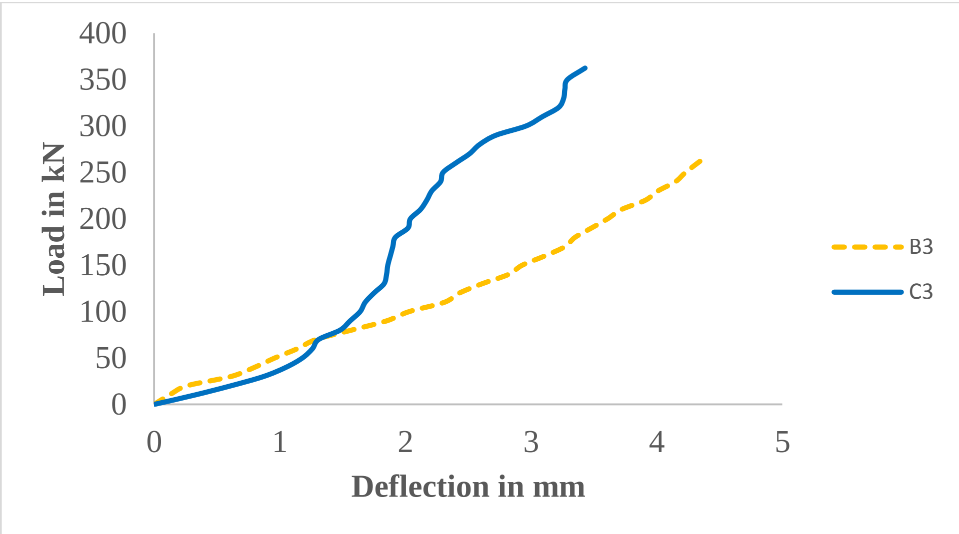

Figure 5-8Load-mid span deflection curve for B3 and C3

The load carrying capacity of specimen C3 was increased by 37% and 11% as compared to the un-strengthened specimen B3 and the control beam, respectively.

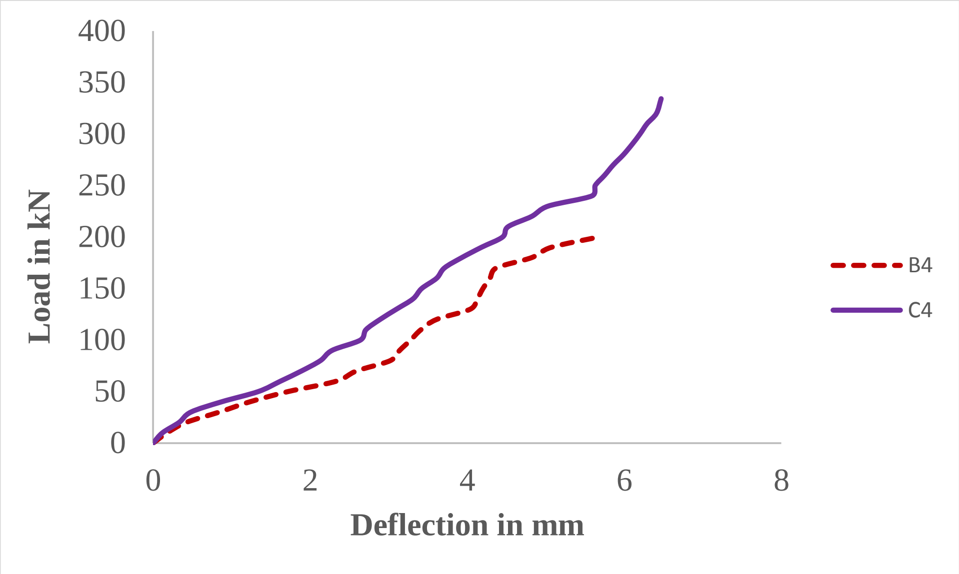

Figure 5-9Load-mid span deflection curve for B4 and C4

The load carrying capacity was increased by 66% from the un-strengthened beam of same size of opening and by 2% from the control beam.

Table 5-1Summary of experimental results

Specimen	Failure Load (KN)	Deflection at Failure Load (mm)	Load increase (%)	First cracking load	Increase in first crack load (%)
CB	329.13	2.24	Reference	120	Reference
B1(Φ110mm)	299.37	2.81	-9	110	9
B2(Φ160mm)	241.35	4.66	-27	50	59
B3(110 x110mm)	264.61	4.37	-20	70	42
B4(160 x 160mm)	201.08	5.69	-39	45	63
C1(Φ110mm)	425.13	3.51	30	-	-
C2(Φ160mm)	340.14	2.24	4	-	-
C3(110 x110mm)	362.41	3.43	11	-	-
C4(160 x 160mm)	334.29	6.47	2	-	-

Even under the presence of holes, load carrying capacity of deep beam strengthened with GFRP have been increased significantly, especially for beam type C1 (an increment of 30% and 42% was achieved with respect to CB and B1, respectively).

As shown in the above table, if the size of the opening is less than 110mm diameter, the reduction in load carrying capacity of the beam is less than 10%.

As the size of the circular openings of un-strengthened beams increase, the load carrying capacity was decreased from 9% - 27% (B1 and B2) and 20% - 39% (B3 and B4) for square openings. The strength gained by the application of GFRP sheets was in the range of 4% - 30% (C1 and C2) and 2% - 11% (C3 and C4) for circular and square openings, respectively.

In terms of the shape of the opening, beams with square openings showed significant reduction as compared to circular openings which consists of four sharp corners which is subjected to high stress concentration that leads to cracking and failure of the beam.

Significant reduction in load carrying capacity can be prevented (especially in the case of B4), even if the dimension of the opening size is large (comparing B4 and C4 with the control beam).

CHAPTER 6 CONCLUSIONS AND RECOMMENDATIONS

6.1 CONCLUSIONS

This research is done on the shear strengthening of reinforced concrete deep beams with and without openings using glass fiber reinforced polymer GFRP composites. A total of nine reinforced concrete deep beams, a solid control beam and beams with circular and square openings with same quality of concrete and reinforcement details are casted and tested. Four beams were strengthened using gelcoat white, general purpose resin, catalyst, mat and woven fiber glasses with a thickness of 3mm. based on the results of this experimental investigation, the conclusion of this study can be summarized as follows:

1. The presence of web openings had great effects on the beam capacity and its behavior and causes 39% reduction in shear capacity of the deep beam.
2. The load carrying capacity of all strengthened beams with GFRP is higher than the un-strengthened beams and the control beam. Externally bonded with GFRP sheets are very effective to increase the shear strength of deep beams with openings.
3. Comparing in terms of shape of the openings, the presence of square openings causes disturbances in the natural flow path of stress which leads to high stress concentration and early cracking at the corners of square openings. Therefore, circular opening is the most suitable to be provided in RC deep beams.
4. At the ultimate load, all un-strengthened deep beams are failed by shear and strengthened deep beams by rupture and de-bonding of GFRP sheets along with crushing of concrete.

6.2 RECOMMENDATIONS

The following areas are to be considered for future research:

1. Strengthening of reinforced concrete deep beam by placing of the openings at shear and flexure zones.
2. Shear strengthening of reinforced concrete deep beams with other strengthening materials such as carbon fiber reinforced polymer, etc.
3. Using strong adhesive such as epoxy can prevent the rupture of GFRP sheets. Bolts and nuts can be used to avoid de-bonding of GFRP sheets.

REFERENCES

[1] ACI Committee 318, Building Code Requirements for Structural Concrete (ACI 318-02) and Commentary (ACI 318R-02).

[2] The European Standard, Design of Concrete Structures(prEN1992-1-1),November 2002.

[3] Swami P.S, Patil S.S, Kore P.N. Behavior of concrete deep beams with high strengthen reinforcement. Department of Civil Engineering, Solapur University, Solapur, India.

[4] AbolfazlArabzadeh, Reza Aghayari, Ali Reza Rahai. Investigation of experimental and analytical shear strength of reinforced concrete deep beams. International Journal of Civil Engineering, Volume 9,No 3. September 2011.

[5] Saeed Ahmed Al-Sheikh. Flexural behavior of RC beams with opening. An International Journal for the Science and Engineering of Concrete and Building Materials, Vol. 5(2) - June 2014.

[6] S.C Chin, DohShuIng. Behavior of reinforced concrete deep beams with openings in the shear zone. Journal of Engineering and Technology,Vol 6. No. 1 January-June 2015.

[7] Nishitha Nair, Kavitha P.E. Effect of openings in deep beams with varying span to depth ratios using strut and tie model method. IOSR Journal of Mechanical and Civil Engineering (IOSR-JMCE) e-ISSN: 2278-1684,p-ISSN:2320-334X.

[8] Siow Sin Yang. Effect of Openings with various Size and Location on RC Deep Beam. Faculty of Civil Engineering and Earth Resources, University Malaysia Pahang, June 2015.

[9]Waleed A. Jasim, Abbas A. Allawi, Nazar K. Oukaili. Effect of Size and Location of Square Web Openings on the Entire Behavior of Reinforced Concrete Deep Beams. Civil Engineering Journal,Vol.5,No. 1, January 2019.

[10] Haider M. Alsaeq. Effect of opening shape and Location on the Structural Strength of RC Deep Beams with Openings.World Academy of Science, Engineering and Technology, International Journal of Civil and Environmental Engineering,Vol:7, No:6, 2013.

[11] Mohamed M. Rashwan, Aly Abdel Zaher Elsayed Ali Mohamed Abdallah, Mahmoud Abdou Mahmoud Hassanean. Behavior of high performance continuous RC deep beams with openings and its strengthening. Journal of Engineering Sciences, Assiut University, Faculty of Engineering, Vol. 42, No. 5, September 2014.

[12] Sayali Anil Kedge, M.V.Nagendra. Experimental analysis of deep beam strengthened by Glass Fiber Reinforced Polymer Plate. International Research Journal of Engineering and Technology (IRJET), Volume: 05 Issue: 06/June-2018.

[13]Dr. Ban Sahib Abduljalil. Shear Resistance of Reinforced Concrete Deep Beams with Opening Strengthened by CFRP Strips. Journal of Engineering and Development, Vol. 18, No. 1 January 2014, ISSN 1813-7822.

[14] Er. Sheelu Mariam Punnoose, Er. Afia S. Hameed. Experimental Study of Strengthening of RC Deep Beam with Web Opening. International Journal of Innovative Research in Technology (IJIRT), Department of Civil Engineering, Saintgits College of Engineering, Kottayam, Volume 3 Issue 4, September 2016.

[15] F.K Kong. Reinforced Concrete Deep Beams. Department of Civil Engineering, University of Newcastel-upon-Tyne, United Kingdom, 2002.