

**PUNCHING SHEAR BEHAVIOUR OF FRP STRENGTHENED FLAT
SLAB WITH AND WITHOUT GEO-GRID**

A Dissertation Submitted
In Partial Fulfillment of the Requirements
for the degree of

**MASTER OF ENGINEERING
IN
STRUCTURAL ENGINEERING**

Submitted by:
**KUMAR RISHABH
(ROLL NO. 801524015)**

UNDER THE SUPERVISION OF

Dr. A. B. Danie Roy
*Assistant Professor
Deptt. of Civil Engineering*
Thapar University, Patiala



**DEPARTMENT OF CIVIL ENGINEERING
THAPAR UNIVERSITY,
PATIALA-147004
JULY 2017**

DECLARATION

I, hereby declare that the thesis entitled **“Punching Shear Behaviour of FRP Strengthened Flat Slab With and Without Geo-grid”**, submitted as per partial fulfilment of the requirements for degree of Masters of Engineering in Structural Engineering under the department of Civil Engineering, Thapar university, Patiala is my own work under the guidance of Dr. A. B. Danie Roy (Assistant Professor, Civil engineering department) during the academic year 2016 – 17. I confirm that the library may lend of copy of this upon request for academic purposes.

Dated: 11 / 8 / 2017

Kr Rishabh

Kumar Rishabh

801524015

CERTIFICATE

This is to certify that the thesis entitled **“Punching Shear Behaviour of FRP Strengthened Flat Slab With and Without Geo-grid”** being submitted by Kumar Rishabh, roll no. 801524015 is an authentic record of work carried out by the student under my guidance

A. B. Danie Roy

Dr. A. B. Danie Roy

Assistant Professor

Civil Engineering department

Thapar University, Patiala

ACKNOWLEDGEMENT

A dissertation cannot be completed without the help of many people who contribute directly or indirectly through their constructive criticism in the evolution and preparation of this work. It would not be fair on my part, if I don't say a word of thanks to all those whose sincere advice made this period a real educative, enlightening, pleasurable and memorable one.

First of all, I would like to thank IIT Roorkee for providing me a platform to pursue my research work by providing me all the required resources.

A special debt of gratitude is owed to my supervisor, Dr. A.B. Danie Roy and Dr. R.Siva Chidambaram for their constant efforts and keen pursuits, which has remained as a valuable asset for the successful completion of my research work.

I would also like to offer my sincere thanks to the non-teaching staff of IIT Roorkee, Mr. Naveen, Mr. Jindal, Rathna Kumar and all other manpower for helping me carrying out my experimental work.

Sincere thanks to my friends Harpreet Singh, Manikant Singhal, Sahil Kamotra, Sambhav Jain and Shubham Moudgil for their constant motivation and support to pursue my dissertation in this topic.

My parents and all my friends, it is because of their omnipresent love, encouragement and support I could reach my desired goal.

ABSTRACT

The upgradation of the building to satisfy the current demand and to improve the performance of weaker sections of buildings, requires advanced techniques. In particular the lesser reinforcement ratio in flat slabs are prone to punching shear failure when the building is upgraded

It is very difficult to increase the percentage of reinforcement in the existing slab. It requires external strengthening using conventional or advanced technique. The conventional technique increases the cross sectional size and is time consuming and it also effects the adjacent structures element performance.

FRP is a proven material in strengthening work. This study is mainly focussed on the use of GFRP and BFRP in uni-directional and bi-directional to improve the punching shear behaviour of flat slabs with different reinforcement ratios. In order to reduce the strengthening area required, geo grid as reinforcement to FRP is also evaluated only using FRP in UD (uni-direction). The load deflection, stiffness and energy dissipation, crack pattern and failure pattern are the parameters that are evaluated.

CONTENTS

DECLARATION	i
ACKNOWLEDGEMENT	ii
ABSTRACT	iii
CONTENTS	iv-vii
LIST OF TABLES	viii
LIST OF FIGURES	ix-x
CHAPTER 1 INTRODUCTION	1-15
1.1 Historic development	1-2
1.2 About flat slab	2
1.3 Importance of FRP	3-10
1.3.1 Basalt fiber reinforced polymer	4
1.3.2 Glass fiber reinforced polymer	5-6
1.3.3 Carbon fiber reinforced polymer	6-7
1.3.4 Geogrid fiber	7-8
1.3.5 Asbestos fiber	8
1.3.6 Aramid fiber	9
1.3.7 Boron fiber	10
1.4 Different form of fibers	11

1.5 FRP strengthening techniques	11-12
1.6 Civil structural application using FRP	12-13
1.7 Punching shear failure	13-14
1.8 Outline of thesis	15
CHAPTER 2 LITERATURE REVIEW	16-23
2.1 General	16
2.2 Literature review on flat slabs	16
2.2.1 Use of steel in the study of flat slabs	16-17
2.2.2 Effect of different compressive strength of Concrete on punching failure of flat slabs	17
2.2.3 Use of FRP reinforcement in flat slabs	18
2.2.4 Use of FRP sheets for strengthening of flat slabs	18-22
2.2.5 Numerical analysis on the use of FRP on flat slab	22-23
2.3 Research gap	23
2.4 Objective of thesis	23
CHAPTER 3 MATERIALS AND TESTING	24-32
3.1 Cement	24
3.1.1 Cement testing	24
3.1.1.1 Consistency test	24-25
3.1.1.2 Initial setting time	25-26

3.1.1.3 Final setting time	26
3.1.1.4 Specific gravity	26-27
3.2 Fine aggregates	27-28
3.3 Coarse aggregates	28-29
3.4 Reinforcement	29
3.5 Fiber reinforced polymer	29-31
3.6 Water	31
3.7 Epoxy	32
3.8 Mix ratio	32-33
CHAPTER 4 MIXING, CASTING AND CURING OF SPECIMEN	34-39
4.1 Preparation of specimen	34-35
4.2 Reinforcement detailing	35-39
CHAPTER 5 STRENGTHENING OF SLAB	40-41
CHAPTER 6 EXPERIMENTAL PROGRAMME	42-46
6.1 Instrument and set up	42-43
6.2 Failure pattern and observation	44-46
CHAPTER 7 RESULTS AND DISCUSSION	47-52
7.1 Load-Deflection behaviour	47-49

7.2 Stiffness characteristics	50
7.3 Energy absorption characteristics	50-52
CHAPTER 8 CONCLUSIONS	53
REFERENCES	54-56

LIST OF TABLES

Table 1.1	Physical properties of CFRP	7
Table 1.2	Physical properties of Aramid	9
Table 1.3	Physical properties of Boron	10
Table 3.1	Physical properties of cement	27
Table 3.2	Sieve analysis of fine aggregate	28
Table 3.3	Physical properties of fine aggregate	28
Table 3.4	Physical properties of coarse aggregate	29
Table 3.5	Physical properties of BFRP	30
Table 3.6	Physical properties of GFRP	31
Table 3.7	Physical properties of Geogrid fiber	31
Table 3.8	Physical properties of epoxy	33
Table 3.9	Concrete mix proportion	33
Table 4.1	Specimen details	38-39
Table 7.1	Stiffness of slab specimens	50

LIST OF FIGURES

Figure 1.1	A typical image of Basalt fiber	4
Figure 1.2	A typical image of GFRP	5
Figure 1.3	Carbon fiber reinforced polymer	7
Figure 1.4	Uniaxial geo gird fiber	8
Figure 1.5	Asbestos fiber	8
Figure 1.6	Aramid fiber	9
Figure 1.7	Boron fiber	10
Figure 1.8	Flexural strengthening of concrete girder	13
Figure 1.9	Strengthening of a concrete deck using CFRP strips	13
Figure 1.10	Punching shear failure	14
Figure 3.1	Mould prepared for testing	25
Figure 3.2	Vicat apparatus for testing initial setting time	26
Figure 3.3	Glass fiber and Basalt fiber	30
Figure 3.4	Geogrid fiber	32
Figure 4.1	Slab casting formwork	34
Figure 4.2	R/F of 100 mm spacing	35
Figure 4.3	R/F of 120 mm spacing	35
Figure 4.4	R/F of 150 mm spacing	35
Figure 4.5	R/F of 190 mm spacing	35

Figure 4.6	Reinforcement details of 100 mm spacing specimens	36
Figure 4.7	Reinforcement details of 120 mm spacing specimens	36
Figure 4.8	Reinforcement details of 150 mm spacing specimens	37
Figure 4.9	Reinforcement details of 190 mm spacing specimens	37
Figure 5.1	Strengthening of slab using BFRP	40
Figure 5.2	Strengthening of slab using GFRP	41
Figure 5.3	Closer view of BFRP strengthened slab	41
Figure 6.1	Experimental setup	42
Figure 6.2	Punching failure equipment	43
Figure 6.3	Slab under punching load	43
Figure 6.4	Punching shear occurring on top surface of the slab	43
Figure 6.5	Crack pattern in FS 10	44
Figure 6.6	Crack pattern in FS 12	44
Figure 6.7	Crack pattern in FS 15	45
Figure 6.8	Crack pattern in FS 19	45
Figure 6.9	Crack pattern in FS15 BFRP BD	46
Figure 6.10	Crack pattern in FS15 GFRP UD	46
Figure 7.1	Comparison between control specimens slabs	47
Figure 7.2	Comparison between different specimens of 150 mm spacing	48
Figure 7.3	Comparison between different specimens of 190 mm spacing	49
Figure 7.4	Energy absorption comparison between control specimens	51
Figure 7.5	Energy absorption comparison between different FS 15 specimens	51
Figure 7.6	Energy absorption comparison between different FS 19 specimens	52

CHAPTER - 1

INTRODUCTION

In the past few decades, India has made many technological advances in many fields. In the field of construction also many new methods and techniques have been developed in order to enhance the properties of structural elements. Earlier, strengthening of various structural elements were very costly but now due to the introduction of various FRP's it has become a lot cheaper as well as easier to operate. From a structural aspect, the main reason for adding fiber is to improve structural behaviour, as they can help in bridging the cracks. Bridging of cracks helps to increase punching resistance, flexural stiffness and ductility. Punching capacity is an important criteria for the design of flat slabs, as it is always the governing factor in choosing its thickness. Due to these advantages, there is a wide range of recent, current and potential applications of these materials that covers both new and existing structure.

1.1 HISTORIC DEVELOPMENT

The first use of reinforced-concrete slabs supported solely on columns dates back to the early twentieth century. The first structure with slabs supported on columns were realized based on the design made by Hill from the year 1899 to 1901. During 1905 to 1909, Turner used this system on a large number of structures thus proving its safety, and paving the way toward a wider use of this system in the future. Robert Maillart who was a swiss engineer also developed a similar structural system. In the period from 1900 to 1908, various experimental research were conducted on slabs which were supported on columns. In 1909, he patented his structural system and so a warehouse with RC slabs supported on columns which was built in 1910 in Zurich according to his design. Kinnunen and Nylander are considered to be the researchers who laid the foundations for the modern day computation of punching. The results of their research, published in 1960, considerably affected the knowledge and understanding available at that time with regard to punching action modelling, which subsequently resulted in further development of punching models. At that time, the primary objective of the researchers was to increase the resistance of slab against punching.

First recommendations for the design of flat slabs, based on experimental research, were given in the US code for the design of reinforced-concrete structures that was published in 1925. At that time, the primary aim of researchers was to increase the resistance of slabs against punching. Over time, some other requirements were also formulated by researchers. One of them was the deformation capacity or the capacity to prevent full separation of column and slab after punching. New reinforcement systems for protection against punching were being developed in response to formulation of new requirements.

1.2 ABOUT FLAT SLAB

A flat slab is a two way reinforced concrete slab that usually does not have beams and girders and the loads are transferred directly to the supporting columns. It is important as it offers a variety of room layout to the owner and also the false ceiling can be omitted. One of its major advantage is that as no beam is used so floor height will be reduced hence making it more economical. Flat slabs are appropriate for most floor situations and also for irregular column layouts, curved floor shapes, ramps etc. Examples are: solid flat slab, solid flat slab with drop panel, solid flat slab with column head, coffered flat slab, coffered flat slab with solid panels, banded coffered flat slab. Flat slabs that are supported directly on columns, without beams between the columns, generally transfer a significant concentrated load that affects a relatively small area. The critical element of this system is the slab to column connection because of the concentration of shear stress that is generated in the connection zone, and due to the slab punching risk. The punching shear denotes slab failure in the zone, where the concentrated load is applied. There are different types of flat slab constructions such as -

- Simple flat slab
- Flat slab with Drop Panels
- Flat slabs with Column Head
- Flat slab with both Drop Panels and Column Head

The most significant parameters influencing the punching strength of slabs are primarily the compressive strength of concrete, reinforcement ratio, mechanical characteristics and type of reinforcement used, size and geometry of columns, size effect, and effective depth of the slab.

1.3 IMPORTANCE OF FRP

In many parts of the world, corrosion of steel reinforcement is a major durability problem, leading to structural degradation and leading to costly repairs. So FRP has emerged as of the most promising technology in construction to overcome the problem of corrosion. Use of FRP composites for construction of new structures and rehabilitation of existing structures has increased significantly over past decade.

The strengthening of structural members with composite materials such as glass fibers, geo-grid fibers have received a lot of attention. Reduced material cost, coupled with labour saving inherent with its light weight have made FRP an attractive alternative. As nowadays due to corrosion there has been an increase in the demand of retrofitting and strengthening of various structural elements. Some of the most important elements that suffer from corrosion in concrete structure are slabs. It has become very difficult to use reinforcement as a strengthening element on an existing building. Hence FRP plays an important role in enhancing the strength of an existing building, as it is not only cheaper but also can be easily installed and gives good results. There is also a potential that FRP laminates can improve the shear capacity of reinforced concrete slabs.

Shear failure occurs suddenly and can be catastrophic, especially in seismic zone. So the benefits from strengthening existing slabs for improved capacity or structural modification can be great. FRP composites are used to repair and strengthen reinforced structural members, especially slabs and beams. Strengthening of slabs with FRP is simple and does not require excessive labour and does not change the appearance of the slab. Various types of fibers used nowadays are-

- Basalt Fiber Reinforced Polymer (BFRP)
- Glass Fiber Reinforced Polymer (GFRP)
- Carbon Fiber Reinforced Polymer (CFRP)
- Geo Grid Fiber
- Asbestos Fiber
- Aramid Fiber
- Boron Fiber

1.3.1 Basalt Fiber Reinforced Polymer (BFRP)

Basalt fiber is a material made from extremely fine fibers of basalt, which is composed of the minerals plagioclase, pyroxene, and olivine. It is similar to fiberglass, but have better mechanical properties than fiberglass and is significantly cheaper than carbon fiber.

Basalt Fiber is made from a single material, crushed basalt from a carefully chosen quarry source. Basalt which contains low iron content and high acidity is considered desirable for fiber production. The first attempt to produce Basalt Fiber was done in the United States in 1923.

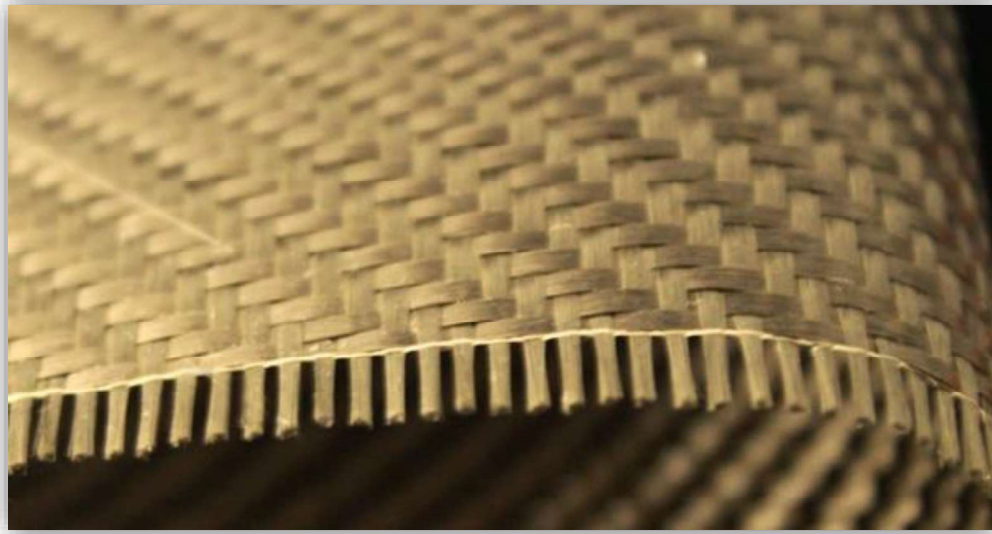


Fig. 1.1: A typical image Basalt Fiber (Basalt.Today)

Some of the common uses of Basalt Fiber are-

- Car bodies
- Lamp posts
- Ship hulls
- Sports equipment
- Heat protection
- High pressure vessels
- Speaker cones

1.3.2 Glass Fiber Reinforced Polymer (GFRP)

Fiberglass (or fibreglass) is a type of fiber-reinforced plastic where the reinforcement fiber is specifically glass fiber. They are randomly arranged, flattened into a sheet (called a chopped strand mat), or woven into a fabric. Fiberglass is unique in its strength and yet it is lightweight. Although glass fiber is not as strong and stiff as composites based on carbon fiber, but 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. Textile glass fibres begin as varying combinations of SiO_2 , Al_2O_3 , B_2O_3 , CaO , or MgO in powder form.

Applications of fiberglass include aircraft, boats, automobiles, bath tubs and enclosures. The glass fibers are made of various types of glass depending upon the use of fiberglass. These glasses all contain silica or silicate, with varying amounts of oxides of calcium, magnesium, and sometimes boron. To be used in fiberglass, glass fibers have to be made with very low levels of defects. An individual structural glass fiber is both stiff and strong in tension and compression—that is, along its axis. Although it might be assumed that the fiber is weak in compression, it is actually only the long aspect ratio of the fiber which makes it seem so, because a typical fiber is long and narrow, it buckles easily. On the other hand, the glass fiber is weak in shear—that is, across its axis. GFRP can be applied to strengthen the beams, columns, 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 loading conditions.

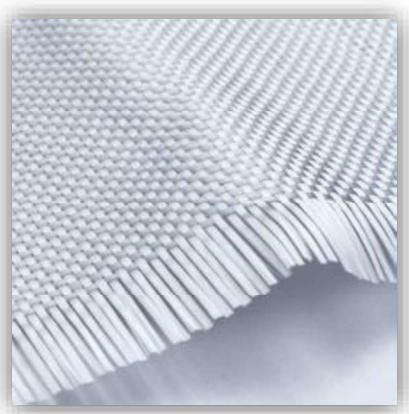


Fig. 1.2: A typical image of GFRP (acmeengineeringco.com)

The most common types of glass fiber used in fiberglass is E-glass with less than 1% w/w alkali oxides, mainly used for glass-reinforced plastics. The basis of textile grade glass fiber is Silica SiO_2 . Although pure silica is a perfectly viable glass and glass fiber, it must be worked with at very high temperatures, which is a drawback unless its specific chemical properties are needed.

1.3.3 Carbon Fiber Reinforced Polymer (CFRP)

Carbon fiber is an extremely strong and light fiber reinforced plastic which contains carbon fibers. CFRP's can be expensive to produce but are used where high rigidity and strength to weight ratio is required. In the case of CFRP, the composite consists of the matrix and the reinforcement. In CFRP, the reinforcement is the carbon fiber which provides strength and the matrix part is usually the polymer resin which helps in binding the reinforcement. The high modulus of carbon fiber makes it suitable to replace alloys such as titanium and aluminium. The carbon fiber is an anisotropic material, and its transverse modulus is an order of magnitude less than its longitudinal modulus. The material has a very high fatigue and creep resistance.

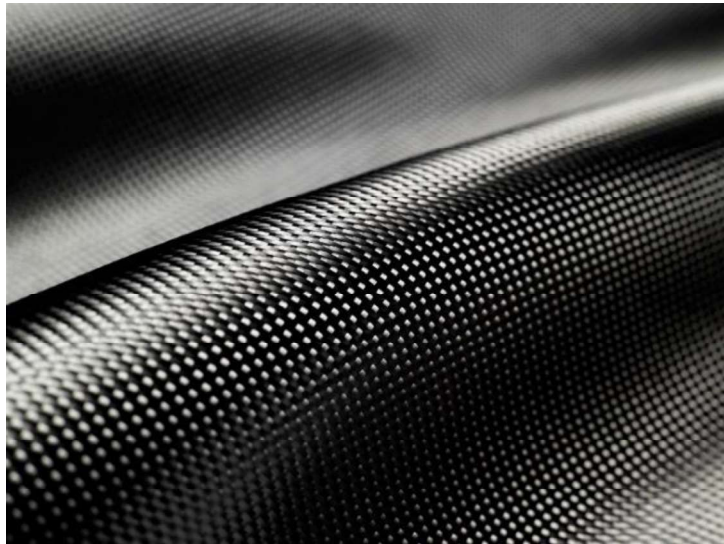


Fig. 1.3 Carbon fiber reinforced polymer (carbonfiberstar.com)

Table 1.1: Physical properties of CFRP

Typical Properties	High Strength	High Modulus	Ultra-High Modulus
Density (g/cm ³)	1.8	1.9	2.0-2.1
Young's Modulus (GPa)	230	370	520-620
Tensile Strength (GPa)	2.48	1.79	1.03-1.31
Tensile Elongation (%)	1.1	0.5	0.2

1.3.4 Geo-Grid Fiber

A geo-grid is geo-synthetic material used to reinforce soils and similar materials. Geo-grids are commonly used to reinforce retaining walls, as well as sub-bases or sub-soils below roads or structures. Soils pull apart under tension. Compared to soil, geo-grids are strong in tension. Geo-grids are commonly made of polymer materials, such as polyester, polyvinyl alcohol, polyethylene or poly propylene. They may be woven or knitted from yarns, heat-welded from strips of material, or produced by punching a regular pattern of holes in sheets of material, then stretched into a grid. The product is bought into the market by giving them an additional coating of either bituminous material or a polyvinyl chloride or a latex. This choice varies with the manufacturer of geo-grids. Mainly there are three types of geo-grids and for the first time it was invented in the United Kingdom in 1982. The geo-grid sector is not only active in the manufacturing of new products but also in providing technical information to aid the design engineers. There are several major markets for geogrids. These are base reinforcement, earth retaining wall construction including veneer stabilisation, the segmental retaining wall market, embankment reinforcement and pile cap platforms. Biaxial geogrids are primarily used in base reinforcement applications, while the uniaxial geogrids are often used in the other markets.

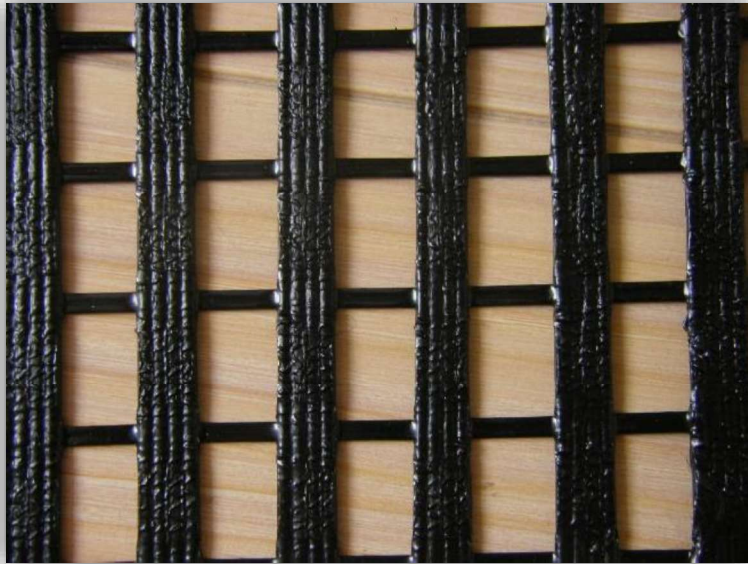


Fig. 1.4: Uni-axial Geo-Grid Fiber (www.geosynthetics.com.cn)

1.3.5 Asbestos Fiber

Asbestos consists of six naturally occurring silicate minerals and are commonly known by their colour such as brown asbestos, white asbestos and green asbestos. Some of the important properties of asbestos fibers are- sound absorption, average tensile strength, affordability, and resistance to fire, heat, and electricity. When asbestos is used for its resistance to fire or heat, at that time fibers are often mixed with cement or woven into fabric or mats. Due to all these desirable properties, asbestos fiber became widely used.

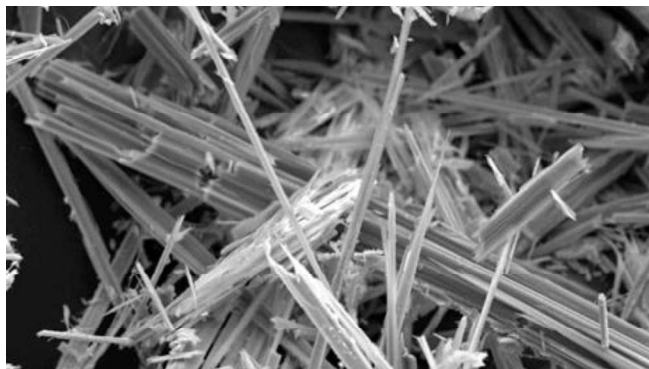


Fig. 1.5: Asbestos fiber (asbestoshub.com)

1.3.6 Aramid Fiber

Aramid fibers are a class of heat-resistant and strong synthetic fibers. Mainly they are used in aerospace and military applications, for ballistic-rated armor fabric and ballistic composites, in bicycle tires, and as an asbestos substitute. Some of its important characteristics are:

- Good resistance to abrasion
- Good resistance to organic solvent
- Sensitive to acids and salts
- No melting point
- Low conductivity
- Sensitive to ultra violet radiation

Table 1.2: Physical properties of Aramid fiber

Typical properties	Kevlar 29	Kevlar 49
Density (g/cm ³)	1.44	1.44
Young's Modulus (GPa)	83/100	124
Tensile Strength (GPa)	2.27	2.27
Tensile Elongation (%)	2.8	1.8



Fig. 1.6: Aramid fiber (pp-fiber.com)

1.3.7 Boron Fiber

Boron fiber actually predates carbon fiber as a high-modulus reinforcement material. The cost of boron, however, has seen its demise, with its replacement with carbon fiber. They do not differ greatly from glass fiber in tensile strength, but can have modulus five times that of glass. Advantages of boron fibers include high tensile modulus and good resistance under compressive loads to buckling owing to the large fiber diameter.

Table 1.3: Physical properties of Boron

Typical properties	Boron
Density (g/cm ³)	2.54
Young's Modulus (GPa)	400
Tensile Strength (GPa)	40000
Thermal Expansion (PPM/ ⁰ C)	4.5



Fig. 1.7: Boron fiber (specmaterials.com)

1.4 DIFFERENT FORM OF FRP FIBERS

The fibers in general have been oriented to suite different applications based on the different manufacturing process.

- **Roving:** Roving is a group of strands, which are more of uniform product. This is the basic form of commercial continuous fiber. Roving are a grouping of a number of strands are so called as “direct pull” rovings, the entire roving is formed at one time.
- **Woven Framing:** These are similar to roving but differ in the weave type and another orientation based on manufacturing process. The same roving product mentioned is also used as input to woven roving reinforcement. Product is defined by weave type, which can be at 0 and 90 degree; at 0 degree, +45 degree, -45 degree and other orientations depending on the manufacturing process.
- **Mats:** These are two dimensional random arrays of chopped strands. The fiber strands are deposited on a continuous conveyor and pass through a region where thermosetting resin is dusted on them. This resin is heat set and holds the mat together. The binder resin dissolves in the polyester or vinyl ester matrix thereby allowing the mat to conform to the shape of the mould.
- **Combined Products:** Several forms are bonded with each other based on the type of output fiber needed. It is also possible to combine a woven roving with a chopped strand mat. There are several techniques for accomplishing this techniques bond the two reinforcements together with a thermosetting resin similar to that in the chopped strand approach.

1.5 FRP STRENGTHENING TECHNIQUES

The Externally Bonded Reinforcement (EBR) and the Near Surface Mounted (NSM) techniques are most commonly used for the strengthening of reinforced concrete (RC) elements. Near surface mounted (NSM) is one of the most recent and promising strengthening techniques for reinforced concrete (RC) structures. NSM requires no surface preparation work and, after cutting the slit, requires minimal installation time compared to the externally bonded reinforcing (EBR) technique.

- **Externally Bonded Reinforcement (EBR) Technique:** To apply the wet lay-up strips of FRP sheet by EBR technique, the following procedures were executed: (1) on the zones of the beams surfaces where the strips of sheet would be glued, an

emery was applied to remove the superficial cement paste.(2) the residues were removed by compressed air; (3) a layer of primer was applied to regularize the concrete surface and to enhance the adherence capacity of the concrete substrate; and (4) using epoxy resin, the strips of sheet were glued on the faces of the beam. In cases that laminates were applied according to EBR technique, identical procedures to the ones adopted in EBR sheets were followed, but instead of epoxy resin it was used adhesive epoxy to bond the laminates to concrete.

- **Near Surface Mounted (NSM) Technique:** The NSM technique was made up of the following steps: (1) using a diamond blade cutter, slits of 4–5 mm width and 12–15 mm depth were cut on the concrete surface of the elements to strengthen; (2) slits were cleaned by compressed air; (3) CFRP laminates were cleaned by acetone; (4) epoxy adhesive was produced according to supplier recommendations; (5) Slits were filled with the epoxy adhesive; (6) epoxy adhesive was applied on the faces of the laminates; and (7) laminates were introduced into the slits and epoxy adhesive in excess was removed.

1.6 CIVIL STRUCTURAL APPLICATIONS USING FRP

Many pedestrian bridge projects have been constructed throughout the United States using pultruded composite structural shapes. In states vulnerable to high seismic activity, concrete bridge columns are being retrofitted with a composite filament winding to increase ductility. Plate bonding using thin composite laminates to strengthen concrete and steel bridge members has been demonstrated. Composite prestressed piles are being applied to civil and marine structures in some of the coastal states.

The first US advanced composite vehicular bridge superstructure was dedicated into service on December 4, 1996 in Russell, Kansas. The deck panels were shop-fabricated with composite honeycomb cells which are sandwiched between two face sheets. These panels were then joined together with epoxy in the field. Demonstration bridge projects are being developed in other states such as Delaware, West Virginia, Sweden and California. Continued research projects using composite reinforcing bars in concrete slabs are being studied in New Hampshire, Washington, D.C. and Michigan. Composite prestressing tendons and stay cables are being developed in Pennsylvania, Michigan, South Dakota and California.

Fig. 1.8 shows the installation of the flexural strengthening of a RC girder of a building in Poland using CFRP prefabricated strips. **Fig. 1.9** illustrates the crosswise application of a RC deck on the bottom side.



Fig. 1.8: Flexural strengthening of concrete girder



Fig. 1.9: Strengthening of a concrete deck using CFRP strips

1.7 PUNCHING SHEAR FAILURE

Reinforced concrete flat slab structures are used widely in construction projects due to their economic and functional advantages. Punching shear failure in such structures can have catastrophic effects in the case of, for example, multi-storey framed structures and the designer aims to ensure that ductile flexural deformation occurs before the brittle shear failure. Punching shear is a type of failure in reinforced concrete slabs subjected to high localised forces. In flat slab structures it occurs in column support points. This type of failure is catastrophic because no visible signs are shown prior to failure. A typical flat plate punching shear failure is characterized by the slab failing at the intersection point of the

column. This results in the column breaking through the portion of the surrounding slab. This type of failure is one of the most critical problems to consider when determining the thickness of flat plates at the column-slab intersection.

Accurate prediction of punching shear strength is a major concern and absolutely necessary for engineers so they can design a safe structure. Punching shear in flat slab is caused due to support reactions which induces a cone shape perforation starting from the top surface of the slab. It is generally preceded by flexural failure, punching shear failure is a brittle failure mode and risk of progressive collapse requires a higher safety class in structural design. Punching failure may take place due to unconservative design of slab-column connections, slab overloading, and deterioration of strength of concrete and reinforcement.

Research has also been conducted in the past to develop an understanding of why punching shear occurs and how to prevent it. In recent years, the finite element method has been applied to analyze punching shear failure problems. It can be used to develop an analytical model for the punching shear failure analysis of reinforced concrete plates. Furthermore, it has been discovered that punching shear can be prevented by increasing the depth of the concrete floor slabs, or by increasing the diameter of the columns supporting the floor.

The design to prevent punching shear failure proceeds as:

- Check if the concrete is strong enough alone
- If not, check the amount of reinforcement is reasonable
- Design reinforcement if reasonable, if not change the form of structure.



Fig. 1.10: Punching shear failure (stucturemag.org)

1.8 OUTLINE OF THESIS

- Chapter-1 discusses about the Introduction part of the thesis and what are the various properties of FRP's that are being used. Historical background related to it and the study on punching shear failure are being discussed in this section.
- Chapter-2 includes the Literature Review part and describes the various research work done by researchers in this field. This section helps in providing the knowledge on all the previous tests that have been done related to the thesis and provides ground for further research.
- Chapter-3 includes the Materials and its Testing part and how different methods were used. This section lays emphasis on the properties of materials used and describes the mix ratio used during the casting procedure.
- Chapter-4 describes the mixing and casting procedure of the specimens and how they were accumulated in right proportion for the preparation of slab specimens. Reinforcement details of all the specimens are also showed in this chapter.
- Chapter-5 discusses about the Strengthening of Slab using different FRP's. This section highlights the importance of the usage of FRP's and how it should be applied.
- Chapter-6 includes the Experimental Setup part of the thesis and describes the methodology used for the testing of specimens. It highlights about the equipment used and also discusses about the crack formation.
- Chapter-7 discusses about the Results and Discussion part of the thesis and includes various graphs depicting different properties of the specimen such as stiffness and energy absorption. All the results from the experiment are analysed in this chapter.
- Chapter-8 includes the Conclusion part which were gathered after getting the end results and how it helped in enhancing the properties of the tested specimens.

2.1 GENERAL

This chapter will provide an overview of the research work carried out in the last decade to study the effect of various different FRP's when applied on flat slabs and how it effects its strength and other properties. In this chapter we will see how various researchers were able to give different results and conclusions by conducting experimental and analytical tests. Various properties such as flexural strength, ductility, deformation have been discussed in this chapter and how varying reinforcement ratio and thickness affects the punching shear behaviour of different test specimens.

2.2 LITERATURE REVIEW ON FLAT SLABS

2.2.1 Use of Steel reinforcement on flat slabs

Asamoah and Kankam (2008) investigated two-way slab reinforced with steel bars milled from scrap steel. The slabs were supported on all four sides and were tested under central concentrated load. Total sixteen two-way slabs were reinforced with the dimension of 1200 x 1200 x 70 mm. The total percentage of steel reinforcement varied from 1.26 to 1.34. The mix proportion by weight cement, sand and aggregate was 1:2:4. Both monotonic and cyclic loadings were used. In the end the experimental loads under monotonic and cyclic loading were 127% and 98% of theoretical failure loads respectively. Cracking started from the center and then propagated towards the edges.

Elbakry and Allam (2015) did both experimental and analytical study on the punching strengthening of two-way reinforced concrete slabs using external steel plates. Total five slabs were tested of 100 mm thickness under central square patch load of 100 mm size up to failure. One of the slab was control specimen and the other were strengthened using four configurations of square steel plate provided with steel anchor steel studs. The size of the slab was 1200 x 1200 mm. Based on their tests they were able to conclude that strengthening of reinforced concrete slabs using externally bonded steel plates provided with shear studs

proved to be effective. An increase in 15-39% of punching shear capacity of the slabs were obtained.

Nguyen *et al.* (2016) did an experimental study on the punching shear behavior of High Performance Steel Fiber Reinforced Concrete (HPFRC) slabs, without shear reinforcement. The fiber orientation was the main point of consideration. The water binder ratio was kept 21% and the steel fiber volume ratios were varying from 0.8 to 1.6%. The specimen were square in shape of dimension 1000 x 1000 mm with the thickness of 60 mm. The number of slabs that were casted were eight. Based on the experimental results the conclusions that were drawn were that the slabs with 0.8% of steel fiber had much more cracks compared to the slabs with 1.6% of steel fiber. When increasing steel fiber from 0 to 0.8% and to 1.6%, the failure load increased from 87 KN to 125 KN and 168 KN, respectively, which is equivalent to increases of 43% and 93%, respectively.

2.2.2 Effect of different compressive strength of concrete on punching failure of flat slabs

Inacio *et al.* (2015) did an experimental research to study the behavior of punching strength of High Strength Concrete (HSC) flat slabs. Three flat slab specimens were casted using HSC and one slab was prepared using normal concrete which was taken as a reference slab. The specimens were square in shape of dimension 1650 mm with a thickness of 125 mm. The HSC mix prepared was of compressive strength of 130 MPa with a basalt coarse aggregate. The longitudinal reinforced ratio varied from .94% to 1.48%. The end results were that an increase of reinforcement ratio from 0.94% to 1.48% led to an increase in the punching capacity of about 13%.

Caratelli *et al.* (2016) studied the behavior of thin reinforced concrete structure in punching by point load. Three concrete mixes were casted, one was ordinary concrete and the other were light weight concrete using fly ash in one case and in other it was fly ash mixed with fiber reinforced light weight concrete. The slabs were reinforced with 20 mm diameter steel rebars. The load was applied centrally using hydraulic jack with maximum load of 4000Kn. After the experiment it was seen that the adopted fiber reinforced material provides an increase of punching strength of about 48% with respect to an ordinary concrete slab, being equal the compressive strength. A sharp increase of the ultimate displacement and ductility was also recorded.

2.2.3 Use of FRP reinforcement in Flat Slabs

EL-Ghandour *et al.* (2003) did a two phase experimental program investigating the punching shear behaviour of fibre reinforced polymer reinforced concrete (FRP RC) flat slabs with and without carbon fibre reinforced polymer (CFRP) shear reinforcements. The slab was supported through a column stud on a beam. Equal point loads were applied symmetrically downward at eight locations on a circle of diameter of 1.7m. Reinforcement ratio was kept different for different slabs varying from 0.18% to 0.38%. The conclusion that they draw was that the main flexural cracks developed directly above the longitudinal reinforcement of all slabs and led to bond splitting in the slabs with low reinforcement ratios.

Haritos and Hira (2004) did an experimental investigation on the performance of two separate CFRP strengthening schemes which was adopted on two 40% scale model of flat slab bridges.

The performance was gauged using dynamic and static testing. Two CFRP based strengthening systems were applied at separate ends of two multi-span RC flat slab bridge models that had previously been severely damaged from high level loading. Results obtained from the static test program suggested that both of the CFRP based strengthening system showed promise as viable strengthening remedial.

Meisami *et al.* (2015) did an experimental program on two-way flat slab using central loading. He used one of the specimen as control specimen and the other three slabs were strengthened in different ways using FRP fans after casting. For strengthening he used 8, 16 and 24 strengtheners. Slabs of 1200 x 1200 mm and 105 mm thick were constructed. Concrete mix was proportioned for a target compressive strength of 40 MPa with water-to-cement ratio of 0.60 and sand-to-aggregate ratio of 0.45 and the specimens were cured for 28 days in order to get desired strength. It was shown that by this method of strengthening not only there was increase in the shear capacity of slabs but also a change in the failure mode that is from shear failure mode to flexural mode.

2.2.4 Use of FRP sheets for strengthening of Flat Slabs

Harajli and Soudki (2003) did experimental investigation to evaluate the punching shear capacity of interior slab-column connection strengthened with flexible CFRP sheets. Total sixteen slabs of measurement 670 x 670 mm with different thickness of 55 mm and 75 mm and reinforcement ratio 1 and 1.5% were used. The specimens were mounted on to a steel

frame with 40 mm wide pedestals on all four sides and loaded centrally through the column stub with a monotonical increase in load until failure. Based on test results the use of CFRP increases the flexural stiffness and improves the punching shear strength of slabs. The increase in flexural strength varied from 26-68% when CFRP were applied.

Salakawy *et al.* (2004) tested seven full scale reinforced concrete slab-column edge connections which he strengthened using different methods against punching shear. The dimensions of the slab were 1540 x 1020 x 120 mm with square columns (250 x 250 mm). The average reinforcement ratio of 0.75% was used. The openings provided in the specimen were of size 150 x 150 mm with the sides parallel to the sides of the column. He used two techniques for the strengthening of slabs. In his first technique he applied externally bonded FRP sheets on the slab around the column in two schemes with one or two layers of FRP sheets glued to the tension or both tension and compression faces of the slab. In his second technique he applied externally bonded FRP sheets and installed steel bolts through the holes across the slab thickness. Based on his experimental results he was able to draw conclusions that the presence of shear bolts increased the ductility of slab-column connections and it increased the flexural stiffness of the slab and delayed the opening of flexural cracks.

Ebead and Marzouk (2004) did the strengthening of two-way slab using CFRP and GFRP laminates and were evaluated experimentally. Specimens were tested for flexural and punching shear failure. In case of flexural failure, two steel reinforcement ratios were included i.e. - 0.35 and 0.50%. In case of punching shear failure strengthening was done using 1% of steel reinforcement along with CFRP strips. The concrete mixture was designed for an average target cylinder with compressive strength of 35 MPa after 28 days. The tested specimens were square with a 1900 mm side length and 150 mm thicknesses. The test specimens were simply supported along the four edges with corners free to lift and were centrally loaded through the column stub. The conclusions that were drawn from the experimental results were that the flexural strengthening specimens using CFRP strips showed an average gain in load capacity by 40% over the reference specimen. In case of GFRP laminates strengthened specimen showed an increase of 31% in load capacity over the reference specimen. The test results of the CFRP strips used for punching shear-strengthening specimens indicated a small average increase within 9% over the un-strengthened specimens.

Enochsson *et al.* (2006) did the rehabilitation and strengthening of concrete structures using FRP's by applying them externally on the specimen. They were applied where the openings were introduced as they can be easily applied. Laboratory tests were conducted on eleven specimens with openings, loaded with distributed load. Six slabs with opening has been strengthened using CFRP sheets. The slabs used are quadratic with a side length of 2.4 m and thickness of 100 mm. The size of opening used were 0.85 x 0.85 m and 1.2 x 1.2 m.

The results that were drawn from this experiment were that the in case of CFRP strengthened slabs the load carrying capacity was increased by 25-125% as compared to that weakened slab. The numerical analysis also showed good agreement with the experimental results in case of CFRP strengthened slabs.

Sissakis and Sheikh (2007) used an innovative approach for strengthening of reinforced concrete slabs in shear with Carbon Fibre Reinforced Polymer (CFRP) laminates. They carried out their experimental study on 28 square, isotropic two-way slab specimens. The slabs were tested under a vertical monotonically increasing concentric load distributed by means of a 200 mm square by 100 mm thick loading plate. To monitor the displacement of the slab specimens, six linearly variable differential transducers (LVDT) were used. Four to measure the displacement of the supporting structure and two for the displacement of the loading plate. Results from the test showed an increase in punching shear capacity by 80% and ductility by 700% when slabs are being retrofitted using CFRP.

Esfahani *et al.* (2008) studied about the punching shear strengthening of flat slabs using Carbon Fiber Reinforced Polymer (CFRP) sheets. Fifteen specimens of reinforced concrete slabs were prepared and tested. Two of them were kept as control specimen and thirteen were strengthened using CFRP sheets. Four of the strengthened specimens were tested under the cyclic vertical loading. CFRP sheets were used on the tension side of the specimen in two perpendicular directions. Load was applied using hydraulic jack through column stub. For the slab specimen, concrete mixtures based on the design compressive strength of 25 and 50 MPa were used. Reinforcing bars of 12 mm and 10 mm diameter were used. Based on the test results the conclusions were drawn that by using CFRP sheets, in addition to steel reinforcing bars as flexural reinforcement improves the punching shear strength of slabs. The improvement is significant in case of slabs with high strength concrete and low steel reinforcement ratio.

Rousan et al. (2011) strengthened eight reinforced concrete slabs with different layers and configurations of CFRP sheets which were fabricated and tested. The size of the slab specimens were 2440 x 600 x 125 mm. They also used FEM using ANSYS package to simulate the behaviour of test specimen. They were casted using concrete mixture having a slump of 75-125 mm and a 28-day compressive strength of 55 MPa. Based on their experimental test results, externally bonded CFRP are very effective in enhancing the ultimate carrying capacity of reinforced concrete slabs.

Anil et al. (2013) investigated the flexural behavior of one way RC slab with opening and applying CFRP strips for strengthening. Size and location on the slab were the main parameter in the experiment. Square openings with 300 mm, 400 mm and 500 mm were tested, which were located at bending and shear zones. Total thirteen specimens were tested, six without strengthening, six with strengthening and one was used as reference specimen. The dimension of the specimen were 3000 x 1000 x 150 mm. 10 mm wide CFRP strips were used for strengthening. Results obtained from the study were that the strengthening of one way RC slab using CFRP strips increased the stiffness and load carrying capacity of the specimen.

Durucan and Anil (2015) did their study at evaluating the effect of CFRP on the punching shear behavior of two-way reinforced concrete slabs strengthened with CFRP strips with varying size and location. Experiments were conducted on eight specimens with varying size and opening. The size of the specimen was kept 2000 x 2000 x 120 mm. Axial load was applied from the top of square column of size 200 x 200 mm in the center of the specimen. The test specimens were strengthened using four CFRP strips of width 150 mm under the slab, next to the openings in the specimen. The size of the opening was 300 x 300 mm or 500 x 500 mm located at the adjacent or 300 mm far from the central column in a diagonal or parallel position. The results deduced from the experiment were that the maximum displacement was increased by 22% by the effect of CFRP strengthening. Results showed that the CFRP strengthening of two-way RC slabs with varying opening increased the overall punching shear capacity by 55%.

Abdulrahman et al. (2017) investigated the effectiveness of strengthening flat slab column corner connections using CFRP sheets. For the variation in the test they also introduced opening near the slab column intersections. They compared the strengthened specimen with that of un-strengthened one in terms of deflection profile and strain profile etc. The size of

the slabs were 2m x 2m square with a thickness of 80 mm and were attached to four 160 x 160 mm square, 720 mm high columns casted monolithically with the slabs. The target compressive strength was 40 MPa. An opening size of 100mm x 100mm was formed close to each column. From the series of slab tested, it was concluded that the strengthening in slabs without opening increased the ultimate punching shear capacity by 11% while in case of opening ones the increase was by 23%.

2.2.5 Numerical Analysis on the use of FRP on Flat Slabs

Faria *et al.* (2014) did a critical review of the technique for strengthening against punching shear by physical model proposed by Critical Shear Crack Theory (CSCT). This approach allows taking into account the amount, layout and the mechanical behaviour of the bonded FRP's in a consistent manner. CFRP laminates were glued on both the sides of the slab and four slabs measuring 1800 x 1800 x 150 mm were used as reference specimen for comparison. It was seen that the increase in punching strength due to strengthening is not linearly proportional to the amount of FRP laminates and depends on its location, with higher efficiencies for laminates glued near the slab-column connection.

Youm *et al.* (2014) investigated the punching shear capacity of light weight aggregate concrete (LWAC) slabs having low reinforcement ratio. They used non-linear FEM to analyse the failure mechanism of LWAC slabs. Total number of five slabs were constructed using normal concrete and four different types of LWAC. 10% of cement weight was replaced by the fly ash for all mixtures. Four different types of artificially produced coarse light weight aggregate were used in the specimen. In the end results it was found that the angle of punching shear failure surface of LWAC slab with clay spherical shape coarse aggregate was less inclined than that with crushed coarse aggregate. Thus, the shape and the source of coarse aggregate effects the angle of punching shear failure surface.

Aghayari and Moradi (2016) did the modelling of Punching shear failure in Reinforced concrete slabs using non-linear Finite Element Analysis (FEM). They compared their readings with the experimental results they obtained from previous research. In total four slabs were tested one was used as control specimen and the other three were strengthened. Dimension of the control slab was 1200 x 1200 and thickness of 105 mm and it was loaded by a hydraulic jack through 150 x 150 x 30 mm steel plate in the centre of slab. In case of strengthened slabs FRP laminates were used. The results showed that for a control slab and

strengthened specimens an increase varied from 4% to 105% in punching shear capacity is determined.

2.3 RESEARCH GAP

Numerous research works have been done to improve the punching shear strength flat slab using CFRP, GFRP etc. Limited studies have been focussed on improving the punching shear strength of flat slab using BFRP and no study has been done on the application of geo-grid as reinforcement to the FRP in improving mechanical performance of slabs. This study is focussed of reinforcing FRP using geo-grid to avoid the use of higher modulus FRP.

2.4 OBJECTIVE OF THESIS

Objective of thesis work is mentioned in the points below:

1. To estimate the contribution of different FRP on the punching strength of flat slab with different reinforcement ratio.
2. To improve the punching shear performance of moderately reinforced and less reinforced slab using externally bonded FRP.
3. To investigate the efficiency of geo-grid reinforcement to the FRP, to eliminate the need of high FRP ratio for strengthening.

A normal strength concrete mix was employed in the present study. The test specimens were casted using PPC, fine aggregate, coarse aggregate, tap water and steel reinforcing bars. The materials were conformed to the requirements of the specifications given in the Indian Standard codes. The detailed characteristics of the materials are presented below:

3.1 CEMENT

A cement is a binder substance which is used in construction that sets, hardens and adheres to other materials, binding them together. PPC (based on Fly Ash) conforming to IS 1489 (Part 1) was used from single lot for the preparation of concrete mix throughout this study. To prevent the cement from atmospheric effect, it was stored in the laboratory as soon it was received.

3.1.1 Cement Testing

Various tests were conducted on cement before it was used. In order to check the various properties of cement and whether it is suitable to use. Proper care was taken while performing these tests so that accurate values can be obtained.

3.1.1.1 Consistency Test

Standard consistency of a cement paste is defined as that consistency which will permit a vicat plunger having 10 mm diameter and 50 mm length to penetrate to a depth of 33-35 mm from top of the mould. This test helps to determine water content for different tests such as initial setting and final setting test. For consistency test, first take 400 g of cement and place it in the enameled tray. Mix about 25% water by weight of dry cement thoroughly to get a cement paste. Total time taken to obtain thoroughly mixed water cement paste i.e. “Gauging time” should not be more than 3 to 5 minutes. Fill the vicat mould, resting upon a glass plate, with this cement paste. After filling the mould completely, smoothen the surface of the paste, making it level with top of the mould. Lower the plunger gently so as to touch the surface of

the test block and quickly release the plunger allowing it to sink into the paste. Measure the depth of penetration and record it. The amount of water can be varied till we get penetration to a depth of 33-35 mm. Consistency can be calculated by dividing the quantity of water used with the quantity of cement used. In the **Fig. 3.1** a prepared mould is been shown.



Fig. 3.1: Mould prepared for testing

3.1.1.2 Initial Setting Time

Initial setting time is that time period between the time water is added to cement and time at which 1 mm square section needle fails to penetrate the cement paste, placed in the Vicat's mould 5 mm to 7 mm from the bottom of the mould.

Take 400 g of cement and prepare a neat cement paste with 0.85P (where P is the normal consistency value) value of water by weight of cement. Gauge time is kept between 3 to 5 minutes. Start the stop watch at the instant when the water is added to the cement and record this time. Fill the Vicat mould, resting on a glass plate, with the cement paste gauged as above. Fill the mould completely and smooth off the surface of the paste making it level with the top of the mould. The cement block thus prepared is called test block. Place the test block confined in the mould and resting on the non-porous plate, under the rod bearing the needle. Lower the needle gently until it comes in contact with the surface of test block and quick release, allowing it to penetrate into the test block. In the beginning the needle completely pierces the test block. Repeat this procedure i.e. quickly releasing the needle after every 2 minutes till the needle fails to pierce the block for about 5 mm measured from the bottom of the mould and note the time.

Vicat apparatus is shown in the **Fig. 3.2**.



Fig. 3.2: Vicat Apparatus for testing Initial setting time

3.1.1.3 Final Setting Time

Final setting time is that time period between the time water is added to cement and the time at which 1 mm needle makes an impression on the paste in the mould but 5 mm attachment does not make any impression. The procedure for the preparation of mould in final setting is similar to that of previous one. The only difference is that we will replace the needle of the vicat's apparatus by the needle from annular attachment. The cement is considered finally set when upon applying the final setting needle gently to the surface of the test block; the needle makes an impression thereon, while the attachment fails to do so.

3.1.1.4 Specific Gravity

Specific gravity is the comparison between the weight of a volume of a particular material to the weight of the same volume of water at a specified temperature.

Le-Chatelier flask is used for the measurement of specific gravity. Initially flask is dried and then kerosene is used to a point on the stem between zero and 1 ml. Level of the liquid in the flask is taken as initial reading. Then weighted amount of cement is added with the kerosene up to the level of 22 ml mark. Then add the whole cement in the flask and roll the flask

gently so that there is no air bubble on the top surface of liquid. New liquid level is taken as the final reading. The physical properties of the cement are presented and compared in the **Table 3.1**.

Table 3.1: Physical properties of Cement

Characteristic	Result Obtained	Recommended values as per IS 1489 (Part 1)
Grade of Cement	PPC	-
Specific Gravity	2.95	-
Standard Consistency	30%	-
Initial Setting Time	45 min	30 min
Final Setting Time	210 min	600 min

3.2 FINE AGGREGATE

Fine aggregate are basically sand won from the land or marine environment. Fine aggregate generally consists of natural sand or crushed stone with most particles passing through 9.5 mm sieve. The fine aggregates used for the experimental work is locally procured and conformed to grading zone II. Main function of the fine aggregate is to act as a binder between the coarser ones. Fine aggregates contribute the maximum to the covering up of surface area in concrete. When high performance concrete is required where the strength of concrete is close to the strength of the aggregate, fine aggregate is needed so that there is no weakness in the structure. Mainly fine aggregates are classified on the basis of size and IS classification. Crushed sand stone, Crushed gravel sand and Natural sand are some of the available fine aggregates. Sieve analysis of the fine aggregate is carried out in the laboratory as per IS 383-1870 as shown in **Table 3.2**. Physical properties of fine aggregate are also shown in **Table 3.3**.

Table 3.2: Sieve analysis of Fine aggregates

S.no	IS-Sieve (mm)	Wt. retained (gm)	% retained	% passing	Cumulative % retained
1	4.75	54	5.4	94.6	5.4
2	2.36	39	3.9	90.7	9.3
3	1.18	21	2.1	88.6	11.4
4	600 μ	95	9.5	79.1	20.9
5	300 μ	728	72.8	6.3	93.7
6	150 μ	47	4.7	1.6	98.4
	Total weight taken	1000		SUM	239.1
				Fineness Modulus	2.39

Table 3.3: Physical Properties of Fine Aggregate

Sr. No	Characteristics	Results	Requirement as per IS 383:1970
1.	Water Absorption	1.4%	-
2.	Fineness Modulus	2.39	2.2-2.6
3.	Specific Gravity	2.61	2.6-2.7

3.3 COARSE AGGREGATE

When the aggregate is sieved through 4.75mm sieve, the aggregate retained is called coarse aggregate. Gravel, cobble and boulders come under this category. The maximum size aggregate used may be dependent upon some conditions. In general, 40mm size aggregate used for normal strengths and 20mm size is used for high strength concrete. Physical properties of coarse aggregate are shown in **Table 3.4**.

Table 3.4: Physical Properties of Coarse Aggregate

Characteristics	Requirements as per IS 383:1970	Results Obtained
Fineness Modulus	5.5-8	7.15
Specific Gravity	2.6-2.7	2.70
Density	-	15.2
Water Absorption	-	0.87

3.4 REINFORCEMENT

Reinforcement steel is a steel bar which is used as a strengthener in reinforced concrete. As it is good in tension and helps to hold the concrete in tension. Reinforcing bars of 8 mm diameter were used in this study and the grade of the reinforcement used was Fy-500.

3.5 FIBER REINFORCED POLYMER

FRP is a composite material made of a polymer matrix reinforced with fibres. The fibres are usually glass, carbon, aramid or basalt. FRP can be applied to strengthen the beams, columns and slabs of buildings and bridges. In order to study the effect of FRP on the specimen, three types of FRP's were used in this study i.e.: Glass Fibre Reinforced Polymer (GFRP), Basalt Fibre Reinforced Polymer (BFRP) and Geo-Grid Fibres. In the **Table 3.5, 3.6** and **3.7**, the physical properties of Basalt fiber, Glass fiber and Geo-Grid fiber has been tabulated and in the **Fig. 3.3** and **Fig. 3.4**, FRP's used in this study has been shown.



Fig. 3.3: Glass Fiber and Basalt Fiber

Table 3.5: Physical properties of BFRP

Sr. No	Mechanical Properties	Results
1	Specific gravity	2.7
2.	Tensile Strength (MPa)	2800-4800
3	Elastic Modulus (GPa)	86-90
4.	Strain at Break (mm/mm)	.0315

Table 3.6: Physical properties of GFRP

Sr. No	Mechanical Property	Results
1.	Density (Kg/m ³)	2.6
2.	Bulk Modulus (GPa)	50
3.	Compressive Strength (MPa)	5000
4.	Ductility	0.028
5.	Poisson Ratio	0.23
6.	Tensile Strength (GPa)	85

Table 3.7: Physical properties of Geo-Grid Fiber

Sr. No	Properties	Results
1.	Elastic Modulus (MPa)	40
2.	Tensile Strength (MPa)	0.44
3.	Elongation (%) at maximum load	1.4
4.	Peak Tensile Resistance (KN/m)	0.62

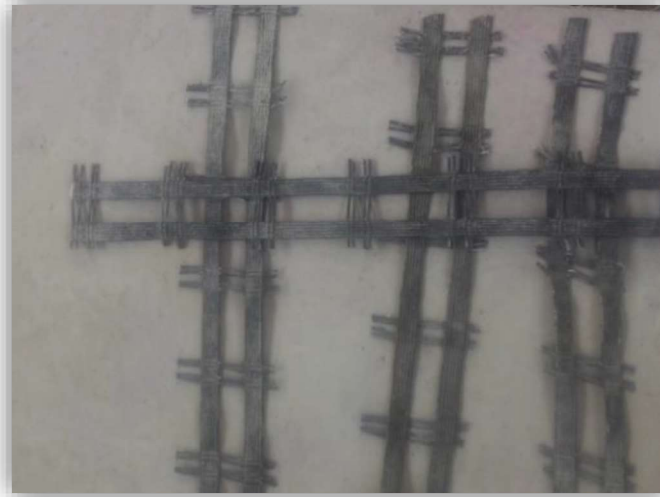


Fig. 3.4: Geo Grid Fibre

3.6 WATER

The water that should be used during the mixing and curing process of the concrete should be free from deleterious materials. Thus potable water is usually used for this purpose. In the present investigation, potable tap water was used during the entire casting and curing period.

3.7 EPOXY

Epoxy is either any of the basic components or the cured end product of epoxy resins. Epoxy resins, also known as polyepoxides are a class of reactive prepolymers and polymers which contain epoxide groups. The high-quality epoxies find wide application in the automotive, construction, heavy engineering, transport, electronics, food and beverage packing, coatings, composites, adhesives, aviation, aerospace and wind energy industries. Epoxy played an important role as it act as a binding agent. It helped in pasting the FRP's on the specimen. The epoxy used consisted of two containers one was base and the other was hardener. Both were mixed in different container and was stirred vigourlsy until it gives greyish colour. Some of its advantages are that the bond it makes with the concrete is very durable and shows good resistance to chemical attack. It exhibits low shrinkage value and act as a good adhesive agent for almost all building materials. Physical properties of epoxy are listed in **Table 3.8**.

Table 3.8: Physical Properties of Epoxy

Sr. No	Properties	Results
1.	Colour	Grey
2.	Mix density (Kg/m ³)	1120
3.	Compressive strength (N/mm ²)	6-7 days
4.	Flexural strength (N/mm ²)	28.1
5.	Tensile strength (N/mm ²)	4-7 days

3.8 MIX RATIO

A normal strength concrete mix was designed and proportioned on the basis of guidelines laid down in IS: 10262 (BIS 2009). This concrete mix was used to fabricate the test specimens. Total numbers of twelve cylinders were casted during the casting procedure. The mix ratio was kept 1:1.5:3. The details of the designed mix proportions along with the 28-days cylinder compressive strengths are given in **Table 3.9**.

Table 3.9: Concrete Mix Proportion

Cement (Kg/m ³)	Water (Kg/m ³)	Sand (Kg/m ³)	Coarse Aggregate (Kg/m ³)	Cylinder Compressive Strength (MPa) in 28 days
450	270	675	1350	20

MIXING, CASTING AND CURING OF SPECIMEN

4.1 PREPARATION OF SPECIMEN

In this study 26 slabs were cast with different reinforcement spacing's i.e. - 100 mm, 120 mm, 150 mm, and 190 mm with 20 mm cover. Cylindrical specimens were prepared to estimate the compressive strength of concrete used. The quantities of various ingredients of the concrete viz. cement, sand, coarse aggregate and water were kept ready for the required proportions of casting. The size of the slabs was of 780 x 830 mm with a constant thickness of 70 mm. The mix design ratio was kept as 1:1.5:3 with 0.45 water cement ratio. A polythene sheet was kept at the bottom to avoid direct contact of concrete with the ground surface. Bricks were used as formwork while casting of the slabs as shown in the **Fig. 4.1**.



Fig. 4.1: Slab casting formwork



Fig. 4.2: R/F of 100 mm spacing



Fig. 4.3: R/F of 120 mm spacing

Fig. 4.2- 4.5 shows the different reinforcement configuration used in the study. Proper measures were taken in order to keep the spacings equal in all the cases. Thin binding wires were used for fixing the reinforcements with one another



Fig. 4.4: R/F of 150 mm spacing



Fig. 4.5: R/F of 190 mm spacing

4.2 REINFORCEMENT DETAILING

Detailing helps in providing clear information about the specimen and helps in providing an overview of the specimen. In the **Fig. 4.6**, **Fig. 4.7**, **Fig. 4.8** and **Fig. 4.9** the plan and sectional view of the 100 mm and 120 mm spacing specimen are shown respectively. The detailed configurations of specimens are presented in **Table 4.1**.

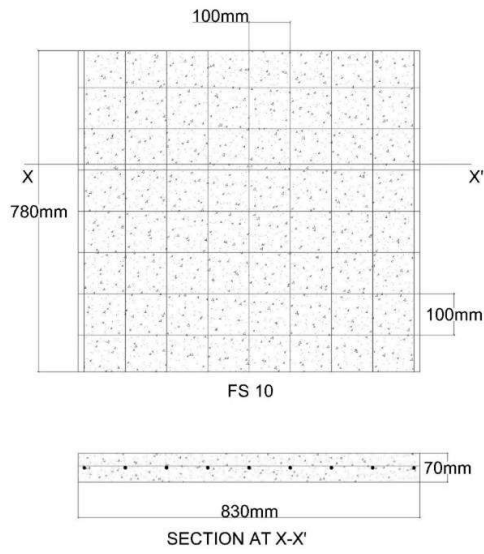


Fig. 4.6: Reinforcement Details of 100 mm spacing specimen

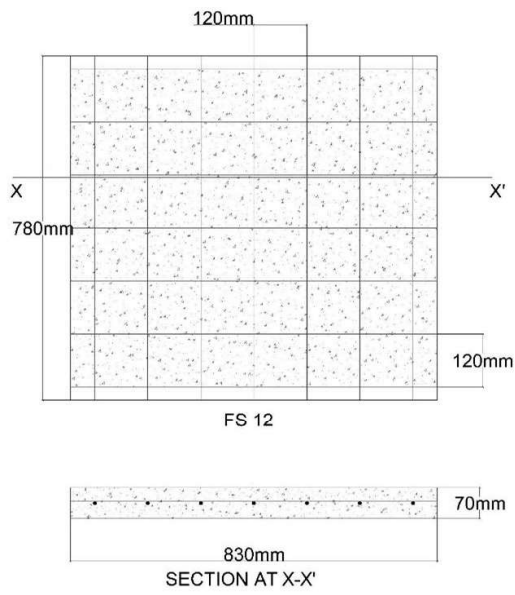


Fig. 4.7: Reinforcement Details of 120 mm spacing specimen

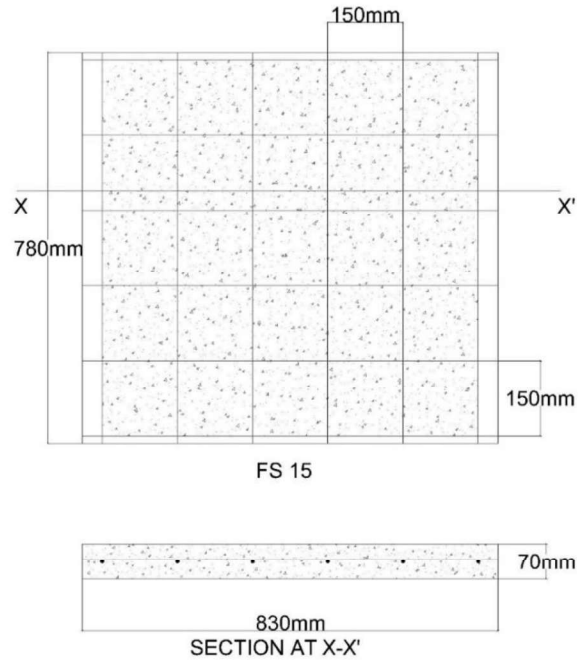


Fig. 4.8: Reinforcement Details of 150 mm spacing specimen

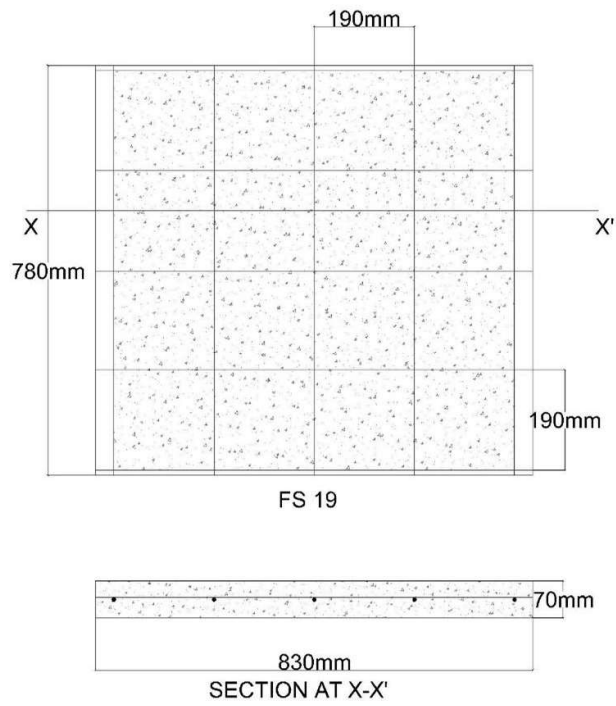


Fig. 4.9: Reinforcement Details of 190 mm spacing specimen

Table 4.1: Specimen Details

Designation	SPACING(mm)	SIZE(mm)	THICKNESS(mm)	FIBER USED
FS 10	100	780 x 830	70	Control
FS 10	100	780 x 830	70	Control
FS 12	120	780 x 830	70	Control
FS 12	120	780 x 830	70	Control
FS 15	150	780 x 830	70	Control
FS 15	150	780 x 830	70	Control
FS 19	190	780 x 830	70	Control
FS 19	190	780 x 830	70	Control
FS 15 GFRP UD	150	780 x 830	70	Glass Fiber in one direction
FS 15 GFRP UD	150	780 x 830	70	Glass Fiber in one direction
FS 15 GFRP BD	150	780 x 830	70	Glass Fiber in two directions
FS 15 GFRP BD	150	780 x 830	70	Glass Fiber in two directions
FS 15 GFRP GG UD	150	780 x 830	70	Glass Fiber and Geo Grid in one direction
FS 15 GFRP GG UD	150	780 x 830	70	Glass Fiber and Geo Grid in one direction
FS 15 BFRP UD	150	780 x 830	70	Basalt Fiber in one direction
FS 15 BFRP UD	150	780 x 830	70	Basalt Fiber in one direction
FS 15 BFRP BD	150	780 x 830	70	Basalt Fiber in two directions

FS 15 BFRP BD	150	780 x 830	70	Basalt Fiber in two directions
FS 15 BFRP GG UD	150	780 x 830	70	Basalt Fiber and Geo Grid in one direction
FS 15 BFRP GG UD	150	780 x 830	70	Basalt Fiber and Geo Grid in one direction
FS 19 GFRP UD	190	780 x 830	70	Glass Fiber in one direction
FS 19 GFRP UD	190	780 x 830	70	Glass Fiber in one direction
FS 19 GFRP GG UD	190	780 x 830	70	Glass Fiber and Geo Grid in one direction
FS 19 GFRP GG UD	190	780 x 830	70	Glass Fiber and Geo Grid in one direction
FS 19 BFRP GG UD	190	780 x 830	70	Basalt Fiber and Geo Grid in one direction
FS 19 BFRP GG UD	190	780 x 830	70	Basalt Fiber and Geo Grid in one direction

*FS-Flat Slab, 10-100 mm spacing, 12-120 mm spacing, 15-150 mm spacing, 19-190 mm spacing, UD-Uni directional, BD-Bi directional, GFRP-Glass Fiber Reinforced Polymer BFRP-Basalt Fiber Reinforced Polymer, GG-Geo Grid Fiber

STRENGTHENING OF SLAB

A total of 18 slabs were strengthened using GFRP, BFRP and Geo-Grid on the tension face of the slab. Twelve slabs of 150 mm spacing and six slabs of 190 mm spacing were strengthened. FRP having 70 mm width was used in one direction (UD) as well as in both the directions (BD). Complete grinding of surface has been done prior to strengthening to have better contact surface for strengthening. Compressed air was used for the removal of dust particles from the surface of the slab.



Fig. 5.1: Strengthening of slab using BFRP

Fig. 5.1 shows the bi-directional strengthening technique using BFRP has been used in both the directions with a spacing of 85 mm and 100 mm. Along the longer side, 85 mm spacing was kept whereas, along the shorter side 100 mm was kept.

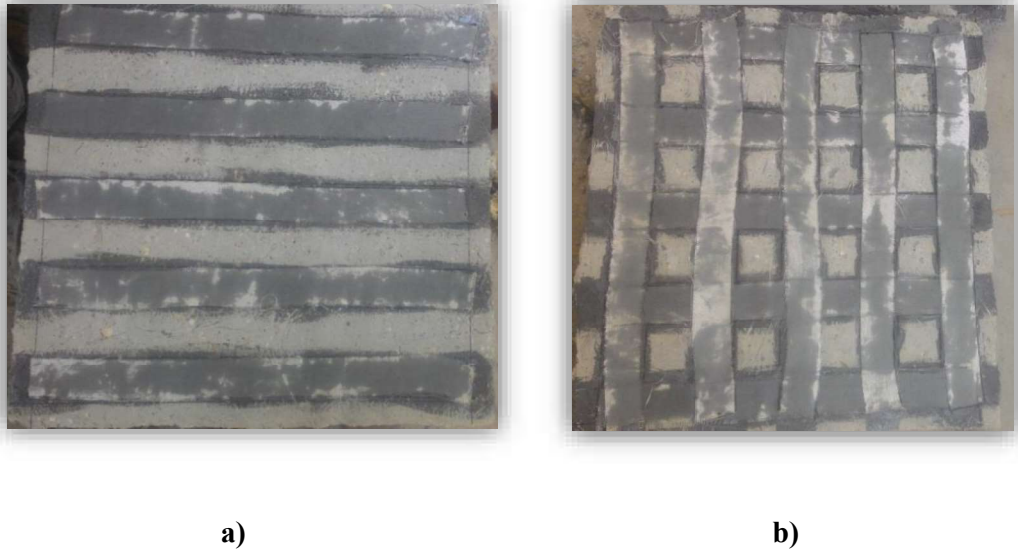


Fig. 5.2: Strengthening of slab using GFRP

Fig. 5.2(a) shows the GFRP strengthened slab in uni-direction i.e. - along the longer side of the slab. **Fig. 5.2(b)** shows the GFRP strengthened slab in bi-direction. The closer view of strengthened slab is shown in **Fig. 5.3**. All air bubbles in the fibers were driven out by rolling a roller on the FRP after affix. The strengthened slab was left for curing for at least 7 days.



. Fig. 5.3: Closer view of BFRP strengthened slab

EXPERIMENTAL PROGRAMME

6.1 INSTRUMENT AND TEST SETUP

All the slabs were tested under flexural testing machine and a controlled test was carried out to study the behaviour of punching shear failure with and without FRP's. A frame was used to give support to the slabs on all the four corners. The ends of the slabs were free to lift upwards as there was no anchorage applied to hold them down. Rate of loading was kept 200 N/s while applying the loads. The testing machine was load controlled and can also measure deflection developed at each increasing load within the specimen. In the **Fig. 6.1**, the experimental set-up is shown.

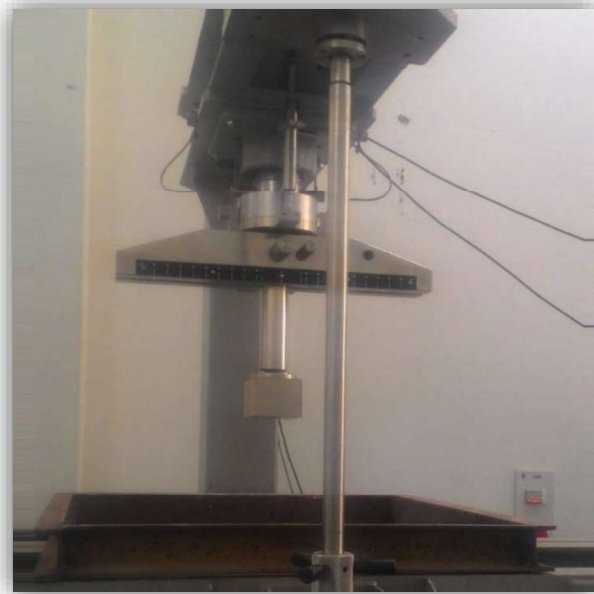


Fig. 6.1: Experimental Set up

The maximum loading capacity of the instrument was 400 KN. The dimension of the frame used to give support to the specimen was 900 x 800 mm and the dimension of the punching failure equipment shown in the **Fig. 6.2** was 100 x 100 x 150 mm.



Fig. 6.2: Punching Failure Equipment



Fig. 6.3: Slab under punching load

The loading speed was kept constant and the test was carried out till the complete failure occurs. The punching failure initiated from the compression side of the specimen as initial cracks were visible on the top surface of the specimen.



Fig. 6.4: Punching shear occurring on top surface of the slab

6.2 FAILURE PATTERN AND OBSERVATION

The simply supported slabs were subjected to a central concentrated load, the central area undergoes maximum punching shear as well as maximum bending moment. The brittle nature of concrete allows early crack formation in the tension face of the slab and as the load increased diagonal crack were also formed. Finally all the control specimens exhibits punching shear failure with different perimeter at the tension face.

The spacing of reinforcement mainly offers resistance to applied load and diagonal crack formation. The brittle nature of concrete allows the cone penetration to form and finally exhibits punching shear failure with various denseness in cracks as depicted in Figures. Higher the spacing higher the perimeter area, which shows that the closer spaced slabs are better resistance to punching effect.



Fig. 6.5: Crack pattern in FS 10



Fig. 6.6: Crack pattern in FS 12



Fig. 6.7: Crack pattern in FS 15



Fig. 6.8: Crack pattern in FS 19

In strengthened specimens the FRP offers better resistance to load and deflection and also shows diverse failure pattern compared to control specimens. All the FRP strengthened specimens behaviours are similar according the configuration. In both GFRP and BFRP (UD) strengthened specimens the formations of diagonal crack were noticed during after failure analysis. The punching force has been well resisted and finally experienced FRP rupture failure as shown in Figure. The specimen strengthened with FRP in bi-directional the resistance to deflection is high and hence the stiffness is enhanced. As a result of this lesser crack formation in the tension face has been noticed and finally FRP rupture occurred as depicted in Figure 6.9.

In particular the resistance to load and deflection offered by the externally bonded FRP strengthening is predominant in Type 4 slab specimens. Though the specimen has higher reinforcement spacing the FRP offers better resistance to punching effect and increases the punching shear strength. Finally FRP rupture was noticed in all the FRP strengthened specimens.

The specimen strengthened with GG-FRP shows improved performance in resistance to load compared to UD and BD FRP strengthening system. The provided geo-grid reinforcement of the FRP offer better resistance to deflection and also enhances the efficacy of the FRP and hence the FRP delamination from the substrate was noticed instead of rupture as evidenced in specimens without geo-grid.



Fig. 6.9: Crack Pattern in FS 15 BFRP BD



Fig. 6.10: Crack Pattern in FS 15 GFRP UD

RESULTS AND DISCUSSION

The load-deflection, stiffness and energy dissipation behaviour of slab specimens were estimated from the experimental test results and discussed in the chapter.

7.1 LOAD – DEFLECTION BEHAVIOUR

Figure shows the load deflection graph of control specimens. It is understood that the difference between the ultimate load carrying capacity and deflection is nearly same in first two control specimens CS1 and CS2. This is possibly because of the minor difference in reinforcement ratio. The control specimen CS3 offer less load carrying capacity compared to CS1 and CS2 because of the higher spacing and also offers less peak deflection. The specimen with 190 mm spacing shows 25% lesser load carrying capacity than CS1 and CS2 but shows better post peak deflection. The occurrence of multiple cracks and crack widening in the early stage of loading allows the specimen to fail gradually and hence the specimen provides better post peak deformation compared to closely spaced slab specimens. This load deflection behaviour clearly explains the need of reinforcement ratio in resisting the punching shear in flat slabs.

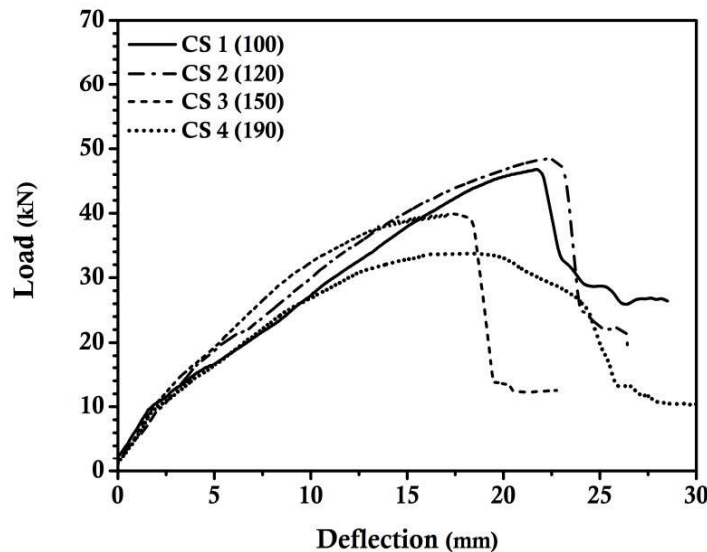


Fig. 7.1: Comparison between control specimen slabs

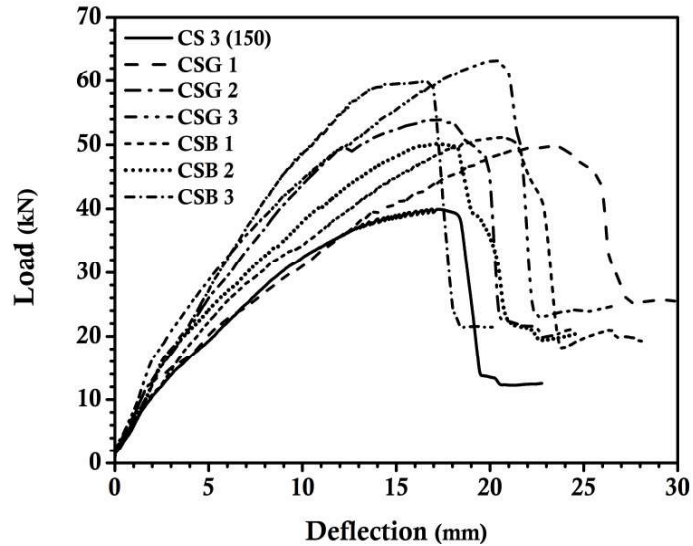


Fig. 7.2: Comparison between different specimens of 150 mm spacing

The load deflection behaviour of Type 3 slab specimens are authenticate the efficiency of FRP strengthening in resisting the punching shear stress. All the strengthened specimens are offers better load carrying capacity than control specimens. In particular the punching shear strength observed is higher than the control specimen CS1, which confirms the effectiveness of FRP strengthening in improving the punching shear resistance of moderately reinforced flat slabs.

The figure unveils that the bi-direction FRP enabled specimens CSG2 and CSB2 shows improved stiffness behaviour as a result of better resistance to deflection and also higher strength than specimen with uni-directional FRP CSG1 and CSB1. It proves that the FRP in bi-direction offers better grid action and also provides good anchorage effect to both direction FRP in improving the strength.

The load – deflection curve of geo-grid reinforced FRP strengthening system enable specimens CSG3 and CSB3 proves the effectiveness of geo-grid reinforcement in improving the resistance to load and deflection without higher percentage of FRP. The stiffness enhancement compared to UD specimens and enhanced deflection compared to BD specimen shows that the geo-grid reinforcement offers better resistance to deflection and load and also provides considerable deflection during severe loading.

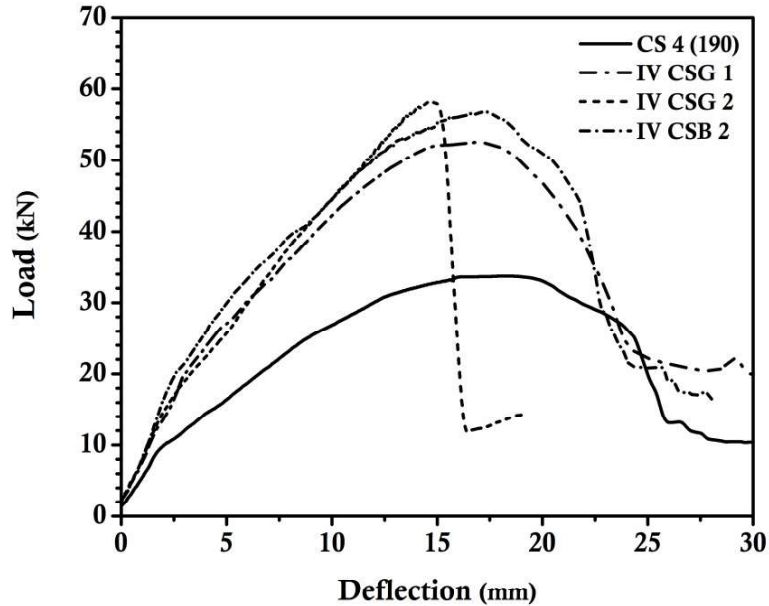


Fig. 7.3: Comparison between different specimens of 190 mm spacing

Fig. 7.3 shows the load deflection of Type 4 specimens. The competent use of externally bonded FRP system in improving the punching shear capacity is evidenced from the graph shown in Figure. In spite of lesser reinforcement ratio, the EBFPR system offers load carrying capacity higher than the specimen with higher reinforcement ratio (CS1 and CS2). It demonstrates the need of FRP strengthening and its success in recuperating the punching shear capacity. The geo-grid reinforced FRP system shows similar kind of response observed in Type 3 specimens.

In the Fig. 7.3, the specimens of 190 mm spacing strengthened with FRP's and the unstrengthened ones are compared. The load carrying capacity before failure is maximum in case of FS 19 GFRP GG UD and is minimum in case of unstrengthened specimen. Geo-Fiber has a high tensile strength and when used with Glass Fiber in one direction, it enhances the load carrying capacity of the specimen.

7.2 STIFFNESS CHARACTERISTICS

Stiffness property of a structural element is the measure of the resistance offered against deformation. The stiffness of a slab at any loading point is the slope of the load-deflection curve at that point.

Table 7.1: Stiffness of slab specimens

Specimen Designation	Stiffness (KN/mm)
FS 10	2.01
FS 12	2.05
FS 15	2.50
FS 19	1.94
FS 15 GFRP UD	2.22
FS 15 GFRP BD	3.17
FS 15 GFRP GG UD	3.15
FS 15 BFRP UD	2.42
FS 15 BFRP BD	3.00
FS 15 BFRP GG UD	3.75
FS 19 GFRP UD	2.94
FS 19 GFRP GG UD	4.07
FS 19 BFRP GG UD	3.29

In the **Table 7.2**, the stiffness of all the slab specimens has been tabulated. It can be seen that the FRP strengthened specimens offered better stiffness than control specimen with higher reinforcement ratio. In particular the FRP in bi-direction shows higher stiffness than UD specimen as a result of better grid action against the deflection. The same stiffness behaviour has been observed with geo-grid reinforced UD FRP strengthening system. It proves that the geo-grid can acts an effecting external reinforcement of FRP and reduces the required area of strengthening.

7.3 ENERGY DISSIPATION CHARACTERISTICS

The energy absorption is calculated from the area under the load-deflection curve. Figure shows the comparative performance of all tested slab specimens. The energy dissipation of control specimens are nearly identical upto 20 mm deflection. According to the peak and post peak performance further enhancement is decided. The failure of CS3 before 20 mm deflection shows least energy dissipation capacity than other control specimens. The lesser punching shear capacity of CS4 shows reduced energy dissipation capacity than other specimens CS1 and CS2.

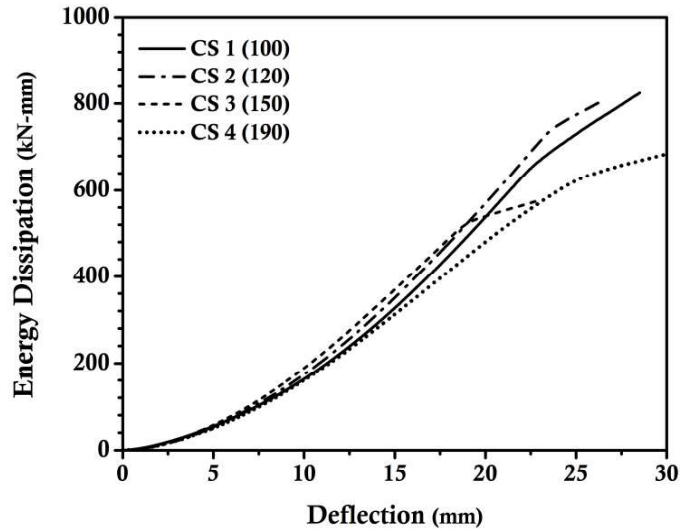


Fig. 7.4: Energy Dissipation comparison between control specimens

Figure shows the influence of FRP strengthening in dissipating the energy. All the FRP strengthened specimen shows 20-40% higher energy dissipation capacity than control specimen CS3. This is also higher than control specimen CS1 and CS2. It proves that the FRP strengthening scheme offers better resistance to load and also dissipates higher energy. The geo-grid enabled specimens also shows higher energy dissipation similar to specimen strengthened with bi-directional FRP. The geo-grid reinforcement reduces the FRP strengthening area without compromising the strength and energy dissipation capacity.

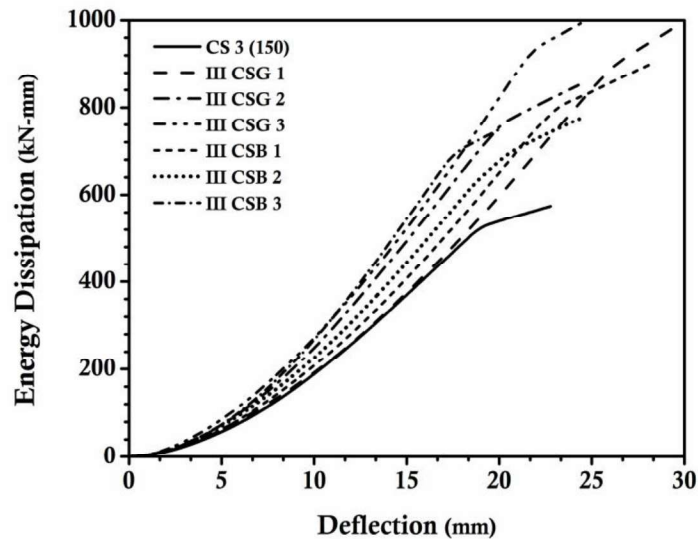


Fig. 7.5: Energy Dissipation comparison between different FS 15 specimens

The success of FRP strengthening in improving performance of flat slabs can be witnessed from the energy dissipation curve shown in Figure. The need of bi-directional FRP is reduced by the use of geo-grid in UD FRP system. It shows more than 80% higher energy dissipation than control specimen CS4 and it is 25% higher than control specimen CS1 and CS2. It proves that the punching shear capacity and energy dissipating capacity of flat slab with lesser reinforcement ratio can be enhanced to slab with higher reinforcement ratio using externally bonded FRP system. The performance can be further elevated with the use of geo-grid reinforcement in UD FRP system.

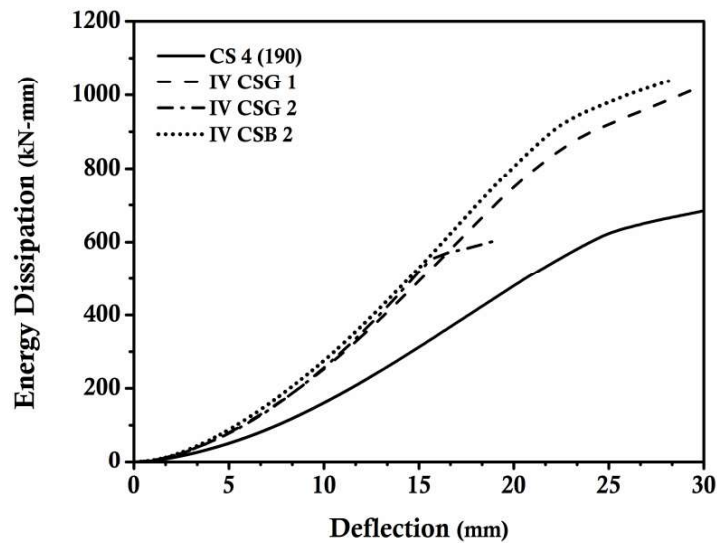


Fig. 7.6: Energy Dissipation comparison between different FS 19 specimens

CHAPTER-8

CONCLUSIONS

From the experimental results following conclusions were drawn:

1. The average increase in the load taking capacity of the strengthened specimens of FS 15 was 34.5% as compared to that of unstrengthened specimen.
2. The average increase in the load taking capacity of the strengthened specimens of FS 19 was 67.5% as compared to that of unstrengthened specimen.
3. The average increase in the load taking capacity of the strengthened specimens of FS 15 and FS 19 as compared to FS 10 came out to be 12% and 15% respectively.
4. The average increase in the stiffness of the strengthened specimens of FS 15 was 41.6% as compared to that of unstrengthened specimen.
5. In case of strengthened specimens of FS 19, the average increase in stiffness is as high as 75% as compared to unstrengthened specimen.
6. The average decrease in the energy absorption of strengthened specimens of FS 15 as compared to unstrengthened one came out to be 27.4%.
7. The average decrease in the energy absorption of strengthened specimens of FS 19 was 51.1% as compared to that of unstrengthened specimen.

REFERENCE

Abdel-Rahman Ahmed M, Nasr Z. Hassan, Adel M. Soliman (2017). “Punching shear behavior of reinforced concrete slabs using steel fibers in the mix”, HBRC Journal.

Aghayari R. and Moradi M.J. (2016). “Improving the Punching Shear Strength of RC Slabs by FRP and Steel Sheets”, Journal of Rehabilitation in Civil Engineering 4-1 01-17.

Al-Rousan R., M. Issa, H. Shabila (2011). “Performance of reinforced concrete slabs strengthened with different types and configurations of CFRP”, Composites: Part B 43 510–521.

Anil Özgür, Nalan Kaya, Onur Arslan (2013). “Strengthening of one way RC slab with opening using CFRP strips”, Construction and Building Materials 48 883–893.

Asamoah Mark Adom, Kankam Charles K. (2008). “Behaviour of reinforced concrete two-way slabs using steel bars milled from scrap metals”, Materials and Design 29 1125–1130.

Caratelli Angelo, Stefania Imperatore, Alberto Meda, Zila Rinaldi (2016). “Punching shear behavior of lightweight fiber reinforced concrete slabs”, Composites Part B 99 257–265.

Durucan Cengizhan Durucan and Anil Özgür (2015). “Effect of opening size and location on the punching shear behavior of interior slab–column connections strengthened with CFRP strips”, Engineering Structures 105 22–36.

Ebead U. and Marzouk H. (2004). “Fiber-Reinforced Polymer Strengthening of Two-Way Slabs”, ACI Structural Journal 101 S-64.

Elbarky Hazem M.F. and Allam Said M. (2015). “Punching strengthening of two-way slabs using external steel plates”, Alexandria Engineering Journal 54, 1207–1218.

El-Ghandour Abdel Wahab, Pilakoutas Kypros and Waldron Peter (2003). “Punching Shear Behaviour of Fiber Reinforced Polymers Reinforced Concrete Flat Slabs: Experimental Study”, ASCE 1090-0268 7:3(258).

El-Salakawy Ehab, Khaled Soudki, Maria Anna Polak (2004). “Punching Shear Behaviour of Flat Slabs Strengthened with Fiber Reinforced Polymer Laminates”, ASCE 1090-0268 8:5(384).

Enochsson Ola, Joakim Lundqvist, Bjorn Taljsten, Piotr Rusinowski, Thomas Olofsson (2006). “CFRP strengthened openings in two-way concrete slabs – An experimental and numerical study”, Construction and Building Materials 21 810–826.

Esfahani M.R., M.R. Kianoush, A.R. Moradia (2008). “Punching shear strength of interior slab- column connections strengthened with carbon fiber reinforced polymer sheet”, Engineering Structures 31 1535-1542.

Faria Duarte M. V., Jürgen Einpaul, António M. P. Ramos, Miguel Fernández Ruiz, Aurelio Muttoni (2014). “On the efficiency of flat slabs strengthening against punching using externally bonded fiber reinforced polymers”, Construction and Building Materials 73 366–377.

Harajli M. H. and Soudki K. A. (2003). “Shear Strengthening of Interior Slab–Column Connections Using Carbon Fiber-Reinforced Polymer Sheets”, ASCE 1090-0268 (7:2)-145.

Haritos N. and Hira A. (2004). “Repair and strengthening of RC flat slab bridges using CFRPs”, Composite Structures 66 555–562.

Inácio Micael M.G., André F.O. Almeida, Duarte M.V. Faria, Válder J.G. Lúcio, António Pinho Ramos (2015). “Punching of high strength concrete flat slabs without shear Reinforcement”, Engineering Structures 103 275–284.

IS: 1489 (PART 1):1991, “Portland Pozzolana Cement Specification”, New Delhi, India: Bureau of Indian Standards.

IS: 383-1970, “Specifications For Coarse and Fine Aggregates From Natural Source For Concrete”, New Delhi, India: Bureau of Indian Standards.

Meisami M. Hasan, Davood Mostofinejad, Hikaru Nakamura (2015). “Strengthening of flat slabs with FRP fan for punching shear”, Composite Structures 119 305–314.

Nguyen Thuc N., Tung T. Nguyen, Withit Pansuk (2016). “Experimental study of the punching shear behavior of high performance steel fiber reinforced concrete slabs considering casting directions”, Engineering Structures 131 564–573.

Sissakis Kyriakos and Sheikh Shamim A. (2007). “Strengthening Concrete Slabs for Punching Shear with Carbon Fiber-Reinforced Polymer Laminates”, ACI Structural Journal 104-S06.

Youma Kwang-Soo , Jung J. Kim b, Jiho Moon (2014). “Punching shear failure of slab with lightweight aggregate concrete (LWAC) and low reinforcement ratio”, Construction and Building Materials 65 92–102.

ORIGINALITY REPORT

12%

SIMILARITY INDEX

%

INTERNET SOURCES

12%

PUBLICATIONS

%

STUDENT PAPERS

PRIMARY SOURCES

1

2%

Fam, A.. "Flexural performance of sandwich panels comprising polyurethane core and GFRP skins and ribs of various configurations", Composite Structures, 201011

Publication

2

2%