ANALYSIS OF PUNCHING SHEAR STRENGTH OF REINFORCED LIGHTWEIGHT CONCRETE FLAT SLAB STRENGTHENED BY GFRP

THESIS REPORT

Submitted by

ANJALI V

ROLL NO.: TKM21CESC04

to

The APJ Abdul Kalam Technological University

in partial fulfilment of the requirements for the award of the Degree

of

Master in Technology

in

Structural Engineering & Construction Management

DEPARTMENT OF CIVIL ENGINEERING

T.K.M. College of Engineering, Kollam

May 2023

DEPARTMENT OF CIVIL ENGINEERING

T.K.M. COLLEGE OF ENGINEERING, KOLLAM

CERTIFICATE

Certified that this report entitled '**ANALYSIS OF PUNCHING SHEAR STRENGTH OF REINFORCED LIGHTWEIGHT CONCRETE FLAT SLAB STRENGTHENED BY GFRP**' is the report of the thesis presented by **ANJALI V**, **Reg No.: TKM21CESC04** during **2022-2023** in partial fulfilment of the requirements for the award of the Degree of Master of Technology in Structural Engineering & Construction Management of the A P J Abdul Kalam Technological University.

Guide	Project Coordinator	Head of the Department
Prof. Hazeena R.	**Dr. Kavitha Madhu.**	**Dr. Sajeeb R.**
Associate Professor	Associate Professor	Professor
Dept. of Civil Engg.	Dept. of Civil Engg.	Dept. of Civil Engg.
TKMCE, Kollam	TKMCE,Kollam	TKMCE, Kollam

DECLARATION

I undersigned hereby declare that the thesis report "Analysis of Punching Shear Strength of Reinforced Lightweight Concrete Flat Slab Strengthened by GFRP" submitted for partial fulfilment of the requirements for the award of the degree of Master of Technology of the APJ Abdul Kalam Technological University, Kerala is a bonafide work done by me under supervision of Prof. Hazeena R. This submission represents my idea in my own words and where ideas or words of others have been included, I have adequately cited and reference the sources. I also declare that I have adhered to academic honesty and integrity ethics and have not misrepresented or fabricated any data, idea, fact, or source in my submission. I understand that any violation of the above will causes disciplinary action by the institute and/or the University and can also evoke penal action from the sources that have thus not been properly cited or from whom proper permission has not been obtained. This report has not previously formed the basis for awarding any degree, diploma, or similar title of any other University.

01/12/2022   ANJALI V.

Kollam

ACKNOWLEDGEMENT

I take this opportunity to express my deep sense of gratitude and sincere thanks to all who helped me to complete the thesis successfully.

I am deeply indebted to my guide, **Prof. Hazeena R.**, Associate Professor, Department of Civil Engineering for her excellent guidance, positive criticism, and valuable comments.

I am greatly thankful to my project coordinator, **Dr. Kavitha Madhu.**, Associate Professor Department of Civil Engineering for her constant supervision as well as for providing necessary information regarding the seminar.

I am greatly thankful to **Dr**. **Sajeeb R**., Professor, and Head of the Department of Civil Engineering, for his kind support.

Finally, I thank my parents and friends who directly and indirectly contributed to the successful completion of my thesis.

ANJALI V.

ABSTRACT

Flat slab structural systems are frequently used in various construction scenarios, such as multistorey buildings, bridges, parking garages, and foundation engineering, for their great economical superiority and ease of construction. The slab-column connection problem may be effectively solved by reducing the weight of RC slabs. The introduction of the reinforced lightweight concrete flat slab is helpful in decreasing the weight of the RC flat slabs which thereby solves the slab column connection problem. Punching shear is a failure mechanism in structural components like slabs and foundations when subjected to concentrated force and it occurs at column support points in flat slabs. FRP system is used, to strengthen LWC slabs subjected to punching shear with some advantages such as corrosion resistance, extraordinary tensile strength, low density, and high strength-to-weight ratio. The influence of GFRP on the punching shear strength of lightweight concrete slabs is examined in this study. Glass fibers possess exceptional characteristics equal to or better than steel in certain forms. Low thermal conductivity, high strength, good electrical insulator, elasticity, incombustible, stiffness, and protection from chemical injury are the distinct properties provided by GFRPs. In this study, numerical analysis of LWC slab strengthening using a GFRP strip was investigated. The difference in punching shear capacity using different orientations, locations, widths and fiber orientations is tested. Evaluations are carried out in terms of punching shear capacity, energy absorption and ductility factor. The numerical analysis found that the strengthened slab improved punching shear capacity as compared to the normal LWC slab. The punching shear strength increases when the strip is placed in the diagonal direction, increasing the number of strips and placing the strip at an offset distance from the loading surface.

Keywords: *Lightweight concrete, GFRP*

TABLE OF CONTENT

Contents   Page no.

LIST OF FIGURES

LIST OF TABLES

CHAPTER 1

INTRODUCTION

1.1 GENERAL

Reinforced concrete building structures are a combination of various structural systems. There were lateral, horizontal, and vertical systems involved. A form of a horizontal structural system called a slab is designed to withstand gravity loads, such as dead and live loads acting on it, and safely transfer those loads to vertical systems, such as columns. Flat slab structural systems are frequently used in various construction scenarios, such as multistorey buildings, bridges, parking garages, and foundation engineering, for their great economical superiority and ease of construction. A flat slab is a reinforced concrete slab that is supported directly by a concrete column without the use of a beam. The slab-column connection problem may be effectively solved by reducing the weight of RC slabs. The introduction of the reinforced lightweight concrete flat slab is helpful in decreasing the weight of the RC slabs, thereby solving the slab column connection problem. Punching shear is a failure mechanism in structural members like slabs and foundations under the action concentrated force and it occurs at column support points in flat slabs. Fibre-reinforced polymer (FRP), an alternative to steel reinforcement, has a low density, excellent tensile strength, and high corrosion resistance. FRP materials are non-conductive, thermally isolating, and exhibit relatively small thermal expansion. Additionally, FRP has a good strength-to-weight ratio. Therefore, if the FRP system is used, to strengthen LWC slabs subjected to punching shear some benefits could be expected. Presently, glass fibers are identified as the most adaptable manufacturing materials among others. They are easily produced from crude materials, which are available in practically unlimited quantities. Low thermal conductivity, high strength, good electrical insulator, elasticity, incombustible, stiffness, and protection from chemical injury are the unique characteristics provided by GFRPs.

1.2 LIGHTWEIGHT CONCRETE FLAT SLAB

1.2.1 Flat slab

Concrete slabs are a type of structural element that is used to build flat horizontal surfaces like floors, roof decks, and ceilings. A slab is generally several inches thick and supported by beams, columns, walls, or the ground. Concrete slabs can be either in-situ poured using

formwork or prefabricated off-site and lifted into place. If reinforcement is necessary, slabs can pre-stressed or the concrete can be placed over rebar positioned set inside the formwork. A flat
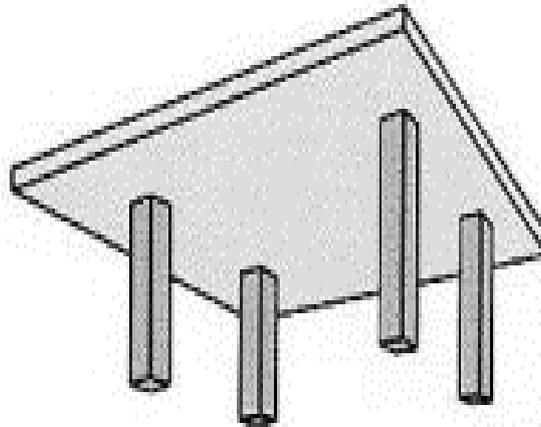
Fig.1 Flat slab (Source: https://www.concrete.org)

slab is a two-reinforced slab that usually does not have beams and girders, and loads are transferred directly to the supporting concrete columns. Flexibility in room arrangement can be achieved i.e., the partition wall can be installed anywhere and gives a variety of room layouts to the owner. As reinforcement detailing of the flat slab is simple, placing reinforcement is made simpler and also eases framework installation. Floor height can be reduced and consequently the building height will be reduced and approximately 10% of the vertical member could be saved using a flat slab.

1.2.2 Lightweight concrete

Lightweight concrete is a particular type of concrete that weighs lighter than conventional or normal concrete. Lightweight concrete typically has a low density. Adding air to concrete is the fundamental idea behind the creation of lightweight concrete. Types of lightweight concrete are lightweight aggregate concrete, No-Fines Concrete, and Aerated concrete. It reduces the dead load of the building and also reduces the cost of shipping and handling as it is simple to handle. Improves workability and provides excellent fire resistance. Comparatively more strong and more durable.

1.2.3 Punching shear of the slab

The punching shear is a shearing failure mechanism that occurs in structural elements like slabs and foundations when concentrated loads are applied to them. Concentrated loads have an impact on a smaller area of the structural elements. In most cases, this reaction is the one from the column acting against the slab. A typical flat slab 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 take into account when figuring out the thickness of flat plates at the column-slab
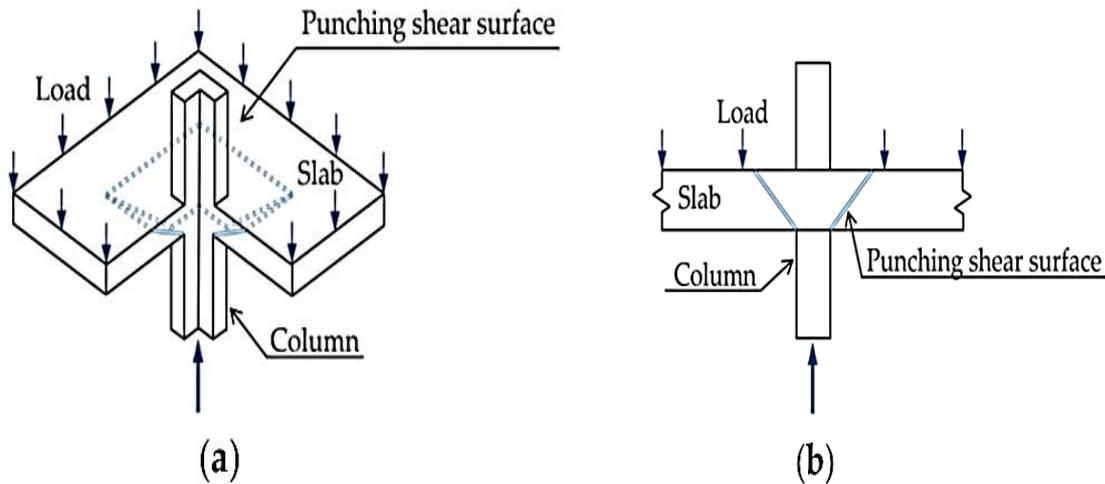
Fig. 2. Punching shear failure (Source: Y Shen et al., 2022)

intersection Engineers must accurately forecast punching shear strength in order to construct a secure structure, which is a serious concern. Punching shear is a phenomenon in flat slabs caused by concentrated support reactions inducing a cone-shaped perforation starting from the top surface of the slab. Although generally preceded by flexure failure, punching shear is a brittle failure mode and the risk of progressive collapse requires a higher safety class in structural design.

1.2.4 Strengthening of slab

There are several methods to strengthen the RC flat slab against punching shear. Strengthening techniques against punching of RC flat slabs could be grouped into four types: enlargement of the support, shear strengthening, flexural strengthening, and post-tensioning systems. For example, the common techniques used for strengthening are drop panels, shear studs, Column capital, shear reinforcement, and FRP strengthening (CFRP, GFRP, BFRP, and AFRP). Fiber-reinforced polymer (FRP), an alternative to steel reinforcement, has a low density, excellent tensile strength, and high corrosion resistance. FRP materials is non-conductive, thermally isolating, and exhibit relatively small thermal expansion. Additionally, FRP has a good strength-to-weight ratio. Therefore, if the FRP system is used, to strengthen LWC slabs subjected to punching shear some benefits could be expected. GFRP is a material with low thermal conductivity, high strength, good electrical insulator, elasticity, incombustible, stiffness, and protection from chemical injury. And also, it is easily available and cost-effective when compared to other FRP materials.

1.3 PROBLEM STATEMENT

Flat slab structural systems are frequently used in various construction scenarios, such as multistorey buildings, bridges, parking garages, and foundation engineering, for their great economical superiority and ease of construction. The slab-column connection problem may be effectively solved by reducing the weight of RC slabs; therefore, the importance of lightweight concrete flat slabs increases. Their popularity is primarily because of the possibility to decrease the dead load of the floor slabs and thereby design a higher number of floors without the need to change the cross-section of the main load-bearing structure elements, such as columns and walls. On the other hand, compared to normal-weight concrete it has higher creep, shrinkage, large deflection, and lower splitting tensile strength were noted. Therefore, if the FRP system is used, to strengthen LWC slabs subjected to punching shear some benefits could be expected. High strength, well resistance to water and chemicals with low cost is the main characteristics of glass fiber. So, there is a need to study the punching shear behaviour of the LWC flat slab after strengthening.

1.4 OBJECTIVES OF THE STUDY

- To compare the punching shear performance of reinforced LWC flab slab with and without strengthened by GFRP strip.
- To study the effect of the configuration, width and location of GFRP strips on the flat slab
- To find the effect of fiber orientation on punching shear performance of reinforced LWC flat slab
- To determine the ultimate load of the flat slab and evaluate ductility factor and energy adsorption based on the load-deflection curve

1.5 ORGANIZATION OF THE REPORT

The first part of the report is an introduction to the punching shear strength of reinforced lightweight concrete flat slabs, and need for the study, and the objectives of the study discussed. The second chapter provides a comprehensive review of literature related to lightweight concrete flat slabs, strengthening by shear reinforcement, strengthening using GFRP, Finite element analysis of flat slabs and the placing techniques of FRP. The third chapter discusses an overview of the basic methodologies used for this study. The fourth chapter presented the validation of the study. The fifth chapter provides modelling and analysis of the study. And finally, a chapter for the conclusion was also provided.

CHAPTER 2

LITERATURE REVIEW

2.1 GENERAL

This chapter provides a thorough review of literature based on lightweight concrete flat slabs, strengthening by shear reinforcement, strengthening using GFRP, Finite element analysis of flat slabs, placing techniques of FRP, bonding of GFRP with concrete.

2.2 LIGHTWEIGHT CONCRETE FLAT SLAB

H.Z. Cui et al. (2012) examined the effects of volume fraction and the characteristics of five different varieties of LWA on the mechanical performance of LWAC. For the prediction model of elastic modulus of LWAC, the effect of volume content, particle density and shape index of LWA was more pronounced while the crushing strength and shape index of LWA showed greater influence on the prediction model for peak strain of LWAC.

H.K. Kim et al. (2012) studied the workability, mechanical, acoustic, and thermal properties of lightweight aggregate concrete with a high volume of entrained air. It has been demonstrated that the lightweight aggregate cellular concrete with the appropriate amount of air-entraining agent has excellent qualities like very high workability, low density, and the proper strength. It can also be used to create architectural members with excellent acoustic shielding and thermal insulating properties.

Investigation by **H. Costa et al. (2012)** on a new method for predicting shrinkage of high-strength lightweight aggregate concrete (2012). Concrete is effectively internally cured when saturated lightweight aggregates (LWAs) are used, which causes less shrinkage. In addition to the factors taken into account by codes, HSLWAC shrinkage is also influenced by the type, quantity, and moisture of LWA.

A. Caratelli et al. (2016) evaluated the punching shear behaviour of light weight reinforced concrete slabs. The punching shear behaviour of slabs made of various concrete mixtures, including those with steel fibre reinforcement, lightweight aggregate, and MSW and found that the steel fibre reinforced concrete looks to be a good and practical solution for increase the punching resistance of ordinary bridge decks. When compared to a typical concrete slab, the

fibre reinforced material used in the analysis increases punching strength by around 48% while maintaining compressive strength.

R.T.S. Mabrouk et al. (2017) found that flexural tensile reinforcement above the column and vertical shear reinforcement in the form of stirrups enhanced the punching capacity of a flat slab. To increase punching shear capacity, stirrups in the two directions of the slab with stirrup widths equal to the column width plus slab thickness were effective.

T. Urban et al. (2019) carried out experimental research on punching shear of flat slabs made of lightweight aggregate concrete. LWC concrete showed a proportionally lower tensile strength than concrete using "Certyd" aggregate, although having a similar compressive strength to that of standard concretes. The investigated specimens' structural behaviour was influenced by their higher brittleness compared to conventional concrete. The extent of fracture growth (crack width) on the specimens' upper surfaces suggests that lightweight aggregate concrete slabs can also adhere to the crack width limitation standards.

M. Said et al. (2020) conducted research on the use of various strengthening methods to increase the punching shear strength of reinforced LWC flat slabs. Punching shear strength is increased by steel bars and studs used as shear reinforcement. When compared to a slab without reinforcement, GFRP rods as shear reinforcement increase the punching shear capacity. The punching shear capacity as well as the ductility were improved by using high-strength steel bolts fixed to the slabs with steel plates as a strengthening approach.

2.3 STRENGTHENING TECHNIQUE OF SLAB

K. Soudki et al. (2012) tested the strengthening of concrete slab-column connections using CFRP strips conducted which are externally bonded to the tension face of the slabs. Higher stiffness values were obtained by strengthening that was positioned close to the columns, while a strengthening that was offset from the column face boosted punching capacity. The skew direction away from the column's perimeter appeared to be the most effective arrangement for CFRP strips, and adding more CFRP strips did not considerably enhance the capacity of the slabs.

An experimental study of drop-panel impacts on reinforced concrete flat slab responses after the loss of corner column conducted by **Kai Qian and Bing Li (2013).** A comparison of the performance of these two series of specimens showed that inserting drop panels into the flat slabs would increase the first peak-resistant capacity by up to 124.7% and significantly reduce

the likelihood of progressive collapse. The experimental findings showed that the initial stiffness and energy dissipation capacity of a flat slab with a drop panel may be increased by up to 117.4% and 85.4%, respectively. The performance of the flat-slab constructions in preventing progressive collapse was greatly impacted by the quantity of slab reinforcement.

M. Hassan et al. (2014) examined the punching shear behaviour of two-way concrete slabs with glass-fiber-reinforced polymer (GFRP) bars as flexural reinforcement and FRP stirrups (glass or carbon) as shear reinforcement. The punched shear strength and deformation capacity of the test slabs were both improved by the FRP stirrups acting as shear reinforcement, and this increase was related to the flexural and shear reinforcement ratios. Also, when FRP stirrups were utilized as shear reinforcement, the performance was improved by lowering the specimens' brittleness.

Strengthening of flat slabs with FRP fan for punching shear is investigated by **M. H. Meisami et al (2015)**. The slabs were strengthened in several ways utilising a cutting-edge method that involved adding FRP fans after casting to improve shear capacity and offer adequate anchorage. According to the findings, this approach can increase maximum loading capacity and deformation capacity while also preventing brittle failure that might happen under vertical stress. Due to the small depth of the slab and simultaneous separation of the end anchoring from the concrete surface, deboning of the FRP fans was the predominant failure mode for flat slabs strengthened by FRP fans.

H. Saleh et al. (2018) investigated the use of FRP materials to strengthen slab-column connections against punching shear**.** The shear capacity of deficient slabs may be increased by strengthening flat slabs against punching shear failure using FRP composites. The location of the shear failure plane is unaffected by the use of FRP sheet/strips for strengthening slabs in the absence of shear bolts. The ductility of the slab is decreased when the area of FRP reinforcement is increased in the flexural strengthening method, and the strengthened slab fails in punching shear mode. To increase the load and deformation capacity, the punching shear strengthening approach beat the flexural method.

H. Saleh et al. (2018) conducted an experimental and numerical study on the punching shear strengthening of RC flat slabs utilising post-installed steel bolts. The findings demonstrated that the strengthening technique raised the load until the slabs flexural failure and increased the slabs ductility in comparison to the control slab. The strengthening approach was also

successful and contributed to changing the failure mode from brittle punching shear to ductile flexural failure mode.

H. Saleh, et al. (2019) explored punching shear strengthening of RC slabs utilizing L-CFRP laminates. The test findings demonstrate that the punching shear and deformation capacities of RC slabs can be greatly increased by employing post-installed L-CFRP laminates. Moreover, the strengthening method can be employed to reduce the risk of rapid structure collapse following punched shear failure by increasing the post-punching deformation of slabs.

Flat slab strengthening techniques against punching-shear **M. Lapi et al. (2019)**. Some techniques comprise incorporating post-installed shear reinforcement, applying external fibre reinforced polymers or a bonded reinforced concrete overlay (BRCO) on the slab top surface, extending the support, and implementing a post-tensioning system. The use of post-installed shear reinforcement raises the failure criterion while also raising the punching strength and ductility. By casting BRCO on top of slabs or attaching FRP onto them, flexural strengthening is accomplished. The support could be made larger by installing a steel capital or casting a new concrete capital. Systems for reinforcing against punching-shear are also available that use flexural and shear post-tensioning.

A review on fiber reinforced polymer laminates for strengthening of rc slabs against punching shear conducted by **O. A. Mohamed et al. (2020)**. To improve the two-way shear capacity, flexural strength, stiffness, and ductility of structurally weak flat slab systems, fibre reinforced polymer (FRP) composite laminates in the form of sheets and/or strips are used. Increasing the two-way/punching shear capability of flat slabs/plates by reinforcing them with fiber-reinforced polymer sheets/strips near the supporting column.

In their examination of the punching shear behavior of flat slabs with various types and configurations of shear reinforcement, **N. Shatarat and D. Salman (2022)** discovered that circular spiral stirrups and continuous rectangular spiral stirrup reinforcement increase punching shear capacity.

Mercimek et al. (2022) compare several strengthening techniques to enhance the punching behaviour of two-way RC flat slabs. Shear studs, fiber-reinforced polymers (FRP), and textile-reinforced mortar (TRM) are the many reinforcing techniques. By comparing the three alternative strengthening techniques' cost and load carrying capacity, the one that used textile reinforced strips produced the best results.

Pre- and post-punching failure performances of flat slab-column joints with drop panels and shear studs studied by **Z. Jiao et al. (2022).** The joint load capacities and pre- and post-punching failure modes were studied. Installing shear studs inside the drop panels increased the punching shear strength when compared to the specimen with a drop panel only. The use of shear studs effectively increased the ductility of the joints, making the punching failure around the column area more ductile even though the post-punching capacity was not greatly improved.

Punching shear strength improved by upward panel in reinforced concrete transfer slabs studied by **S. -M. Kang et al. (2022)**. The use of upward panels in reinforced concrete transfer slab systems can increase punching shear strength while reducing slab thickness, providing superior architectural plan and constructability. This study looked into how upper panels affected the punching shear strength of transfer slabs. The adoption of the upward panel with diagonal reinforcement, as shown by the test results, enhanced the punching shear strength of the of the transfer slab specimens by 100–128%.

2.4 STRENGTHENING USING GFRP

A.K. Panigrahi et al. (2014) investigates an experimental investigation on the performance of RC T-beams strengthened in shear using epoxy bonded bi-directional GFRP fabrics. The shear capacity of RC T-beams can be increased by using external strengthening with GFRP composites, although the effectiveness varies depending on test variables including fibre orientations, number of layers, wrapping, and anchorage schemes. The test results demonstrate that the FRP system's strengthening method can improve the shear capacity of RC T-beams.

GFRP reinforced lightweight concrete slabs' serviceability and ultimate behaviour were examined by **A. Wiater and T. Siwowski in (2020).** Contrasted with code prediction, an experimental test. LWC slabs had much wider cracks and more deflection than NWC slabs with the same reinforcing ratio. The ultimate capacity and post-cracking rigidity were unaffected by the reinforcing arrangement in a significant way. So far, it had an impact on the beginning stiffness.

H. Soltani, et al., (2020) conducted the dynamic performance enhancement of RC slabs by steel fibers vs. externally bonded GFRP sheets under impact loading. It can be concluded from the study of SFRC slabs with non-fibrous RC slabs that SFRC slabs performed better under impact load. Increased use of GFRP layers on the slab's bottom face has a greater impact on

reducing slab displacement than GFRP layers on the top faceunder impact load. There is a direct relationship between the number of GFRP layers and the recorded maximum acceleration.

2.5 FINITE ELEMENT ANALYSIS OF FLAT SLAB

G.J. Milligan, et al., (2020) studied finite element analysis of punching shear behaviour of concrete slabs supported on rectangular columns. The parametric study's findings show that the column aspect ratio alone does not fully account for the influence of column rectangularity on the punching shear behaviour of slab column connections. The ratio of column size to slab depth, denoted as cmin/d (k), has a significant impact on it as well. Finite-Element Analysis of Reinforced Concrete Slabs with Punching Shear Reinforcement

Using the concrete damage plasticity model, **A. S. Genikomsou et al. (2016)** performed finite element simulations of RC slabs and examined the results. The suggested calibrated concrete model, which was used to analyse companion slabs without shear reinforcement, has proven beneficial for simulating the behaviour of shear-reinforced slabs.

Finite element analysis for interior slab-column connections reinforced with GFRP bars using damage plasticity model investigated by **H. Madkour et al (2022).** The numerical study done on 324 models with various design parameters (i.e., the GFRP reinforcement ratio, slab depth, concrete strength, GFRP grade, and column dimensions) on the ductility index of the connections and compared with the same connections that are reinforced with conventional steel reinforcement. The outcomes demonstrate that the suggested CDP model can accurately simulate and predict the overall performance of the GFRP RC slab-column connections.

Parametric finite element analysis of punching shear behaviour of RC slabs reinforced with bolts done by **M. Navarro et al. (2020)**. A number of non-linear numerical models are analysed using ABAQUS to simulate the punching shear effect on reinforced bolt-retrofitted. The shear-bolt radial pattern may be most suitable for retrofitting slab-to-column connections in which the phenomenon of punching shear is probable to occur. Also, it is advised to leave a space around five times the diameter of the shear bolts between the first set of bolts and the face of the column.

M. G. Marques, et al. (2020) explored nonlinear finite element analysis (NLFEA) of reinforced concrete flat slabs with holes. The numerical findings showed that utilising studs enhanced strength while using holes decreased punching shear strength. The prediction

accuracy of the failure loads presented by the numerical method was better than the results predicted by some selected codes.

2.6 PLACING TECHNIQUES OF FRP

Amiri and S. Behzad Talaeitaba (2020) discovered that the grooving approach had a delayed debonding effect and increased the effectiveness of FRP strengthening. All of the EBR specimens have reached brittle shear failure, whereas only three of the EBROG and EBRIG reinforced specimens have experienced shear-flexural failure, proving the superior performance of the EBROG and EBRIG approach method compared to the EBR method.

Torabian, et al (2020) studied the flexural strengthening of flat slabs with FRP composites using EBR and EBROG methods. The experimental findings demonstrated the effectiveness of the EBROG technique in delaying the debonding of CFRP composites utilised for the flexural strengthening of flat slabs. When compared to EBR, the debonding strains in the case of EBROG were significantly higher.

2.7 FIBER-REINFORCED POLYMER

Fiber-Reinforced Polymer Composites: Manufacturing, Properties, and Applications studied by **D. K. Rajak et al. (2019).** In addition to having a high strength to weight ratio, fiber-reinforced polymer composites exhibit excellent qualities such great durability, stiffness, damping property, flexural strength, and resistance to corrosion, wear, impact, and fire. Natural and synthetic fibres are two of the many types of fibres that can be used to create fiber-reinforced composites. The production processes are specified according to the material selection. The remarkable properties of composites, including as resistance to impact, wear, corrosion, and chemicals, have also come to light. Nevertheless, these characteristics depend on the material's composition, the type of fibre used, and the manufacturing method used to make the composite.

H. Fang et al. (2019) investigated the connections and structural applications of fibre reinforced polymer composites for civil infrastructure in aggressive environments. The many benefits of FRP composites highlight their superiority over conventional materials for such specialised applications and support the development of lightweight, highly durable under aggressive environment-resistant civil infrastructure. FRP composites serve as major load-carrying members for such construction.

Tensile capacity of FRP anchors in connecting FRP and TRM sheets to concrete tested by **D.A. Bournas et al. (2015)**. The carbon fibre spike anchor can be utilised in a variety of strengthening applications to prevent premature delamination of FRP and TRM sheets from concrete surfaces, since it is an efficient anchorage device when properly anchored into concrete.

A review on fiber reinforced polymer strengthening of structures by near-surface mounting method conducted by **A Parvin * and T S Shah (2016)**. The high strength and stiffness of composite materials, their non-corrosiveness, and their ease of installation are the key reasons why NSM-FRP utilisation has increased. In comparison to EBR, NSM-FRP strengthening can achieve larger stresses, which allows for a more effective use of the FRP material and an increase in the flexural, shear, and ductility properties of RC beams. NSM-FRP can prevent premature debonding, which is demonstrated in EBR-FRP reinforced structures under flexural and shear loads.

2.8 GLASS FIBRE REINFORCED POLYMER

Experimental research on GFRP bar bond behaviour in conventional and self-consolidating concrete was conducted by **Zemour et al. (2018).** The load capacity, crack pattern, failure mode, and load-deflection response of the SCC beams were comparable to those of their NC counterparts. Beams cast with the SCC had a somewhat weaker connection than beams cast with the NC.

F. Yan and Z. Lin (2016) used FE simulation to examine the bond behaviour of GFRP bar-concrete interface. The surface treatment was the most obvious component influencing the damage evolution, according to comparisons of those bond damage evolution curves. More severe damage development was visible in the plain concrete specimens with grooved surfaces than in the reinforcing GFRP bars with the HW-SC surface addition, the critical bond damage of the FRC specimen was smaller than that of the plain concrete specimen, as well as its corresponding slip.

G. Fava et al. (2016) investigate the bond between GFRP rebars and concrete. Although it can be stated that when dealing with the system of GFRP rebars and concrete the failure occurs due to the peeling of bar rather than the concrete crushing around it, when the pull-out tests on GFRP rebars comparable to those achieved for steel rebars. As the concrete wasn't crushed or

split apart during debonding, this should indicate a reduction in the maximum bond stress as well as a development length independent of the concrete's strength.

Tensile behavior of glass fiber reinforced composite at different strain rates and temperatures studied by **Y. Ou, D. Zhu (2015).** At room temperature, the tensile strength, maximum strain, and toughness increase when the strain rate is increased, whereas the Young's modulus, tensile strength, and toughness decrease as the temperature is raised.

2.9 SUMMARY

Lightweight concrete is an alternative material to normal concrete and can be used for manufacturing flat slabs. The punching shear is a shearing failure mechanism that occurs in structural elements like slabs and foundations when concentrated loads are applied to them. So, the strengthening of slabs is needed to resist the punching shear. Shear strengthening is used as a strengthening technique but it leads to reinforcement congestion at the region of the column. So FRP is an alternative material to steel reinforcement due to its low density, excellent tensile strength, and high corrosion resistance, etc. GFRP is a material with low thermal conductivity, high strength, good electrical insulator, elasticity, incombustible, stiffness, and protection to chemical injury. It has also good bonding with concrete. And the EBROG and EBRIG methods are the most suitable methods for placing FRP. Finite element analysis is efficient and powerful, which can be used to simulate the true punching shear behaviour of flat slabs with reasonable accuracy. But the studies on the punching shear capacity of GFRP-strengthened reinforced lightweight concrete flat slabs are very less. The effect of width and location on GFRP strips on the reinforced LWC flat slab is not studied. Studies on the effect of fiber orientation on the punching shear performance of reinforced LWC flat slabs were not available. Limited research investigated the effect of eccentricity. Study on finite element analysis on GFRP-strengthened reinforced LWC flat slabs is very less. So, which is need to be analyse.

CHAPTER 3

METHODOLOGY

3.1 GENERAL

A lightweight concrete flat slab is considered for analysis. The low cost, quick results, and ability to solve difficult problems make numerical analysis of structures an appealing research solution. The three-dimensional non-linear element slab model is built using commercial software ANSYS Workbench. For conducting the analysis, the first step to validation of ANSYS software is based on the experimental analysis conducted by Said et. al. (2020). Structural modelling of the LWC Flat slab utilising ANSYS Workbench, nonlinear static analysis, parametric study, and result comparison are the processes involved in the study. The parametric analysis was performed to understand the effect of orientation, width, and position of the GFRP strip on the punching shear capacity of the LWC slab. A comparison study based on the ultimate load, energy absorption, and ductility factor of LWC flat slab with and without GFRP strip strengthening gives a detailed evaluation of LWC slab performance. The load-displacement curve is a useful tool for comparing the results. A comprehensive framework of the methodology used to complete this study is shown in Fig 3.1.
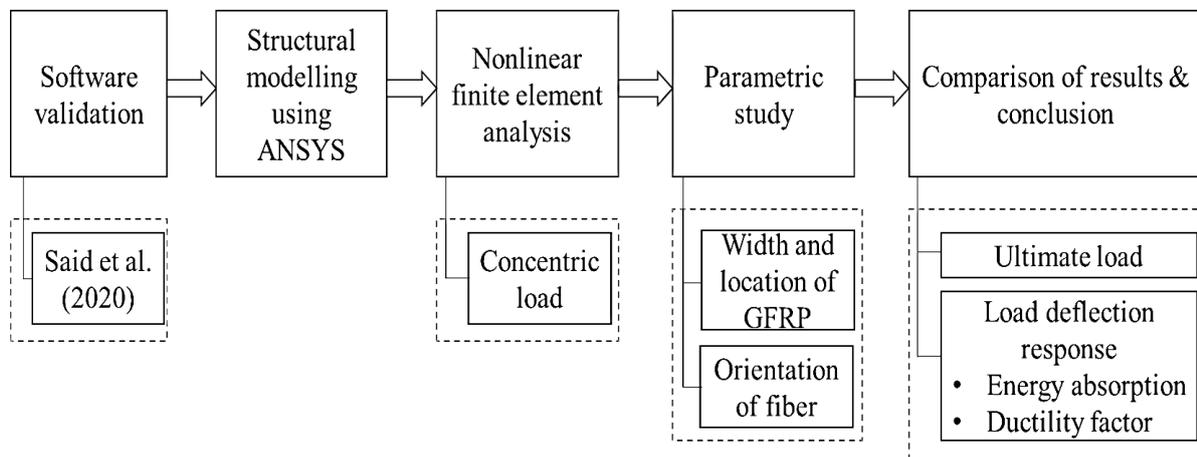

Figure 3.1. Outline of methodology

3.2 NUMERICAL MODELLING

Analytical methods, experimental methods, and numerical methods are three general approaches to solving complex engineering problems. Although analytical approaches provide precise results, they are limited to simple geometries. Experimentation can produce exact

results, but it is expensive and rarely cost-effective. The finite element analysis (FEA) technique, which is a highly versatile and comprehensive numerical tool, can be used to solve engineering problems numerically. The three main components of Ansys, like many other FEA programmes, are the processors, also known as pre-processor, solution processor, and post-processor. The Ansys pre-processor allows users to define materials, construct geometry, and create element mesh. The Ansys processor allows users to solve problems by applying loads and finding solutions. The Ansys post-processor enables the listing of results in tabular form and visualisation. Ansys enables a comprehensive software suite that spans the whole range of physics, providing access to virtually almost any area of engineering simulation that a design process requires. ANSYS is able to create complex engineering simulations that are accurate and realistic in nature by applying a variety of contact methods, time-dependent simulations, and non-linear material models. ANSYS provides the capacity to execute the analysis and integrate various physics into one platform. Similar to how thermal analysis and structural analysis, fluid flow analysis and thermal and structural analysis, etc. The reinforcement is modelled with a link element (Link 180), and the concrete is modelled with solid domains (SOLID65). GFRP is modelled with shell element.

3.3. NONLINEAR STATIC ANALYSIS

The lightweight concrete slab was strengthened by a GFRP strip subjected to non-linear static analysis. **A** nonlinear analysis is an analysis where a nonlinear relation holds between applied forces and displacement. Geometrical nonlinearity, material nonlinearity, and contact are the sources of nonlinear effects. The effect results in a constant stiffness matrix during the load application. The design procedure for nonlinear static analysis is as follows:

Step 1. Newton-Rapson equilibrium iterations were used for nonlinear analysis. A displacement-controlled incremental loading was applied through the centre of the flat slab.

Step 2. The total deformation and force reaction were calculated at the prescribed loaded to give a clear idea about the performance of the LWC slab with and without strengthening. It helps to carry out a comparative study between both slabs.

3.4. PARAMETRIC STUDY

The LWC flat slab strengthened with GFRP strips depends on many parameters like configuration, location, width and orientation of fibre. Investigating the influence of configuration, width and location of GFRP strip on punching shear behaviour of slab. And also

investigate the effect of fibre orientation in the GFRP on the punching shear behaviour of the slab.

3.5. COMPARATIVE STUDY

The analysis results were obtained from the ANSYS software. The reaction force and corresponding deformation were obtained at the prescribed load. The load versus deformation graph were created. From the load vs deformation curve, the energy absorption and ductility factor were calculated. The load versus deformation graph were created. o better understand the improvement in the structural performance of GFRP-reinforced LWC flat slabs, the results of the calculation for strengthened slabs were compared to those obtained for normal LWC flat slabs.

CHAPTER 4

VALIDATION

4.1. GENERAL

M. Said et al, 2020 conducted a study on improving the punching shear strength of reinforced LWC flat slabs using different strengthening techniques. The cracking load, maximum load, load-deflection curves, and load-shear studs strain curves were studied. The control specimen of this literature is going to validate in this study. NLFEA was performed to simulate the tested RC flat slab and the FEA software package ANSYS was used for the analysis. The dimension and the reinforcement details of the slab are shown figure 4.1and the modelled slab in ANSYS shown in figure 4.2. The Material properties of the concrete and steel are provided in table 4.1.
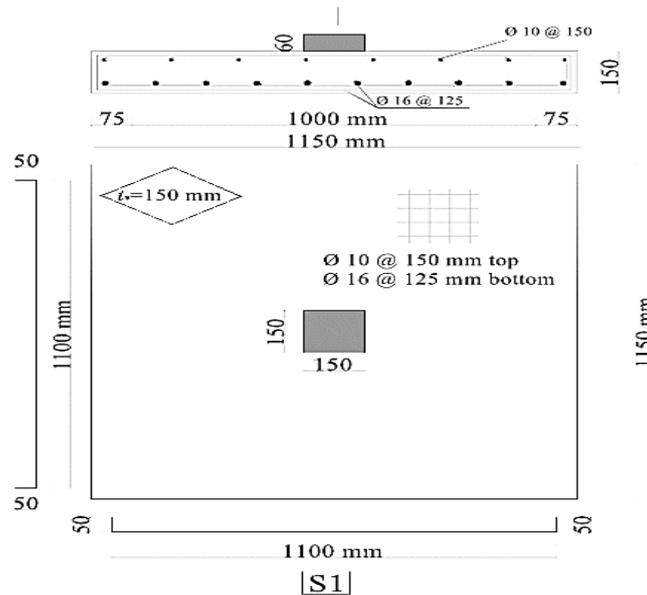
Figure 4.1 Control specimen (Source: M. Said et al, 2020)

Table 4.1 Materials properties (M. Said et al, 2020)

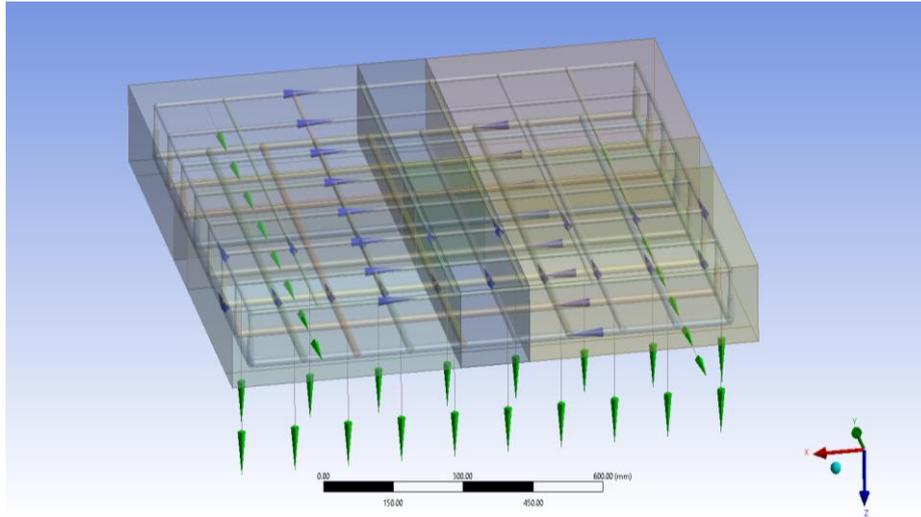| SL.NO.	MATERIAL	PROPERTY
1	Lightweight concrete	Density = 16.50 kN/m^2
		Target strength = 25 MPa
2	Steel	Yield strength = 400 MPa
		Ultimate strength = 580 MPa

Figure 4.2. Modelling of slab

The Slab Concrete Model was tested with a simple support system, where one end was fixed and the other end was sliding. A prescribed displacement of 5.5 mm was applied to the top centre (150x 150mm) area and the reaction force and corresponding total deformation were calculated at the prescribed load. The boundary condition and loading are shown in figure 4.4.
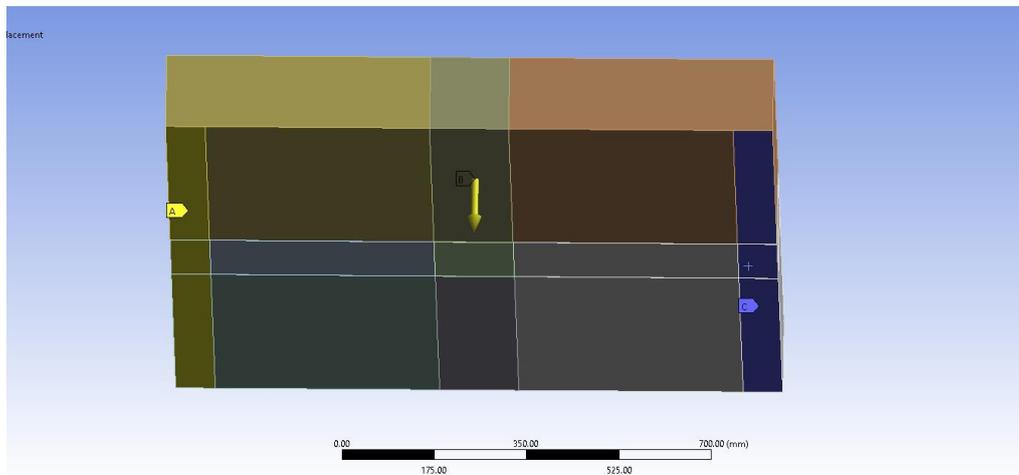

Figure 4.3 Boundary condition and loading condition

4.2 MESH DEPENDENCY STUDY

The Mesh Dependency Study is a research project that looks at the effects of mesh size on the accuracy of numerical solutions for partial differential equations. It studies the impact of mesh refinement on the stability, accuracy, and convergence of numerical solutions. It also examines the effect of mesh size on the computational time and memory requirements of the numerical solutions. The study is used to determine the optimal mesh size for a given problem, in order

18

to achieve the best results with the least amount of computer resources. Table 4.2 shows the mesh dependency study.

Table 4.2 Mesh dependency study

Element size in mm	Number of elements	Total deformation in mm
36	5114	5.499
34	5742	5.597
32	7661	5.583
30	8859	6.10
28	9761	6.10

The Mesh Dependency Study evaluated the effects of mesh size on the accuracy and stability of numerical solutions to partial differential equations. The study tested six different mesh sizes - 36, 34, 32, 31, 30, and 28 mm - and found that the 30 and 28 mm meshes showed the same deformation in the same prescribed description. Based on these results, the study concluded that a 30 mm mesh size should be used for further study, in order to achieve the best results with the least amount of computer resources. The Slab Concrete Model was created in ANSYS Design Modeler according to the dimensions specified in the journal. The concrete parts were modelled with solid domains (SOLID65) and the reinforcements were modelled with link elements (Link 180) and the element order is linear. Figure 4.3 represents the meshed model.
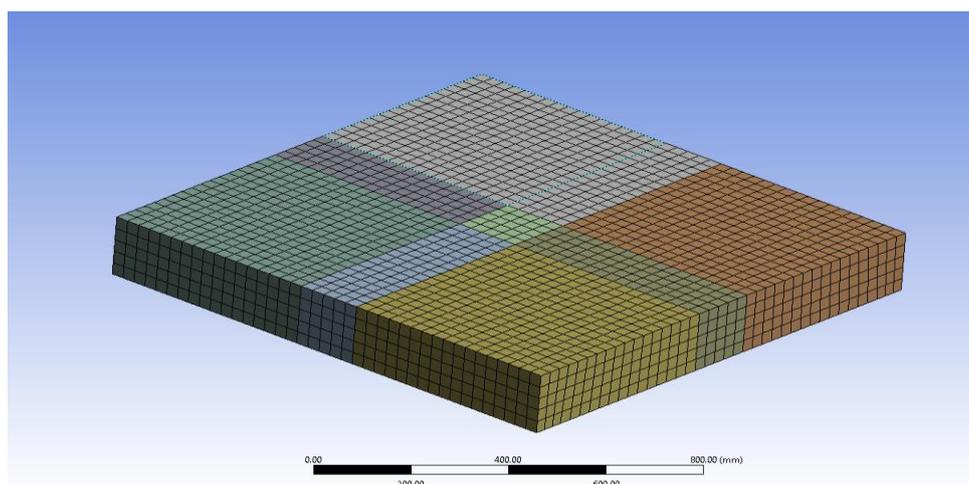

Figure 4.3 Meshed model

After Pre-processing stage of the Slab Concrete Model resulted in a total deformation of 6.1mm. This value was obtained after applying the prescribed displacement of 5.5 mm to the top center (150x 150mm) area. The deformed shape of the lab is shown in figure 4.5. The maximum deflection occurred at the loading surface. The load deflection curve of the slab are shown in figure 4.6.
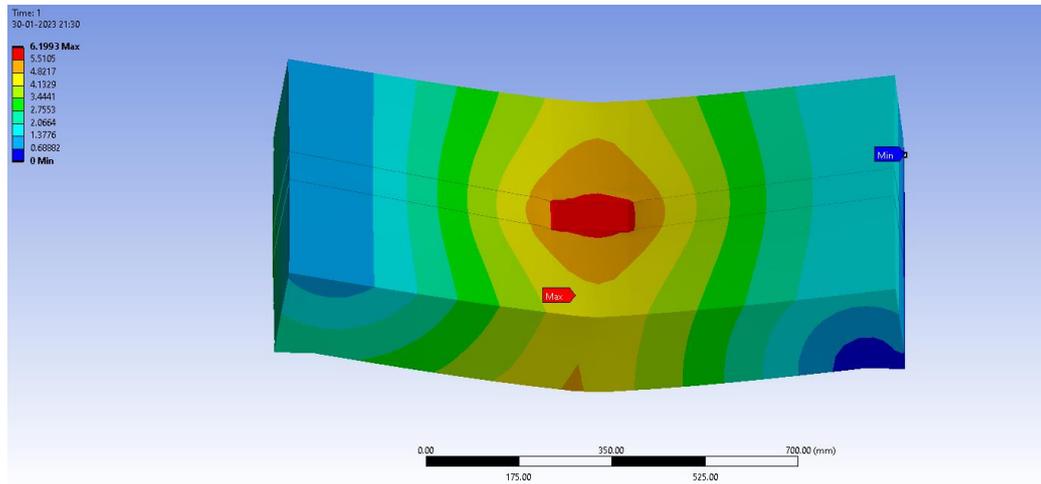

Figure 4.5 Deformed shape of the slab

Figure 4.6 Load vs deformation curve

The ultimate load value and displacement value from the numerical analysis and from the experimental analysis are tabulated below in Table 5.3. The variation of 3.80% and 1.1% are observed in ultimate load and displacement value respectively for mesh size 30. Since the difference is less than 10% the software and model can be used for analysis.

Table 4.3 Percentage of error Table

Experiments	Reaction force (kN)	Deformation(mm)
Group A slab S1 as per the journal	340	6.03
Validated result	353	6.1
Percentage of error	3.80%	1.1%

The numerical model has been validated with the published results based on the experiment conducted by Said et. al. (2020). The most accurate result is obtained when using the mesh size of 30 mm. The percentage of error of 3.80% was obtained while comparing the results of force reaction from journal and model created in ANSYS and the percentage of error for deformation is about 1.1%. The slight difference may be due to the variations in the unknown assumptions made in defining properties of materials and in the defining the interaction between reinforcement and concrete.

CHAPTER 5

GEOMETRIC MODELLING AND ANALYSIS OF STRUCTURE

5.1 GENERAL

Using ANSYS Workbench the geometry of a lightweight concrete flat slab is modelled. The material properties for concrete, steel reinforcement, and GFRP is taken from the literature of M. Said et al, 2020. The punching shear strength value of lightweight concrete slabs with and without strengthening is going to find by model and analyse using ANSYS. The lightweight concrete slab is strengthened using the GFRP strips that are modelled and analysed. The composite member was modelled using the ACP (pre) module. Adding material property in the engineering data section follows creating the model in geometry and then, creating a mesh in the model section. In the setup section, define the composite material fabrics, element orientations, ply layup, etc. The set-up section in the ACP (pre) can be linked to the model section in the static structure, which is shown in figure 5.1. In this section, set up the connection, the boundary conditions, and the loading conditions, then conduct the analysis to obtain the conclusion. In order to investigate how the configuration, location, and width of GFRP strips affect the punching shear performance of strengthened slabs, a series of eleven specimens one reference slab without any strengthening and ten specimens with various GFRP configurations were used.

Figure 5.1 Procedure of analysis

5.2. GEOMETRIC MODELLING

The lightweight concrete flat slab developed in ANSYS is shown in figure 5.2. For the analysis, eleven square slab specimens with dimensions of 1150 x 1150 mm and a total depth of 150 mm were used. The slab specimen's effective depth was determined to be 130 mm. Steel reinforcement bars were employed to reinforce the LWC slab in all specimens; the bottom

reinforcement mesh was 16 mm in diameter and spaced 125 mm apart, while the top reinforcement mesh was 10 mm in diameter and spaced 150 mm apart. Figure 5.3 illustrates the specifics of the ANSYS-developed slab reinforcement. The slab is reinforced with GFRP strips that are 1 mm thick. The GFRP modelled in ACP is shown in Figure 5.4.
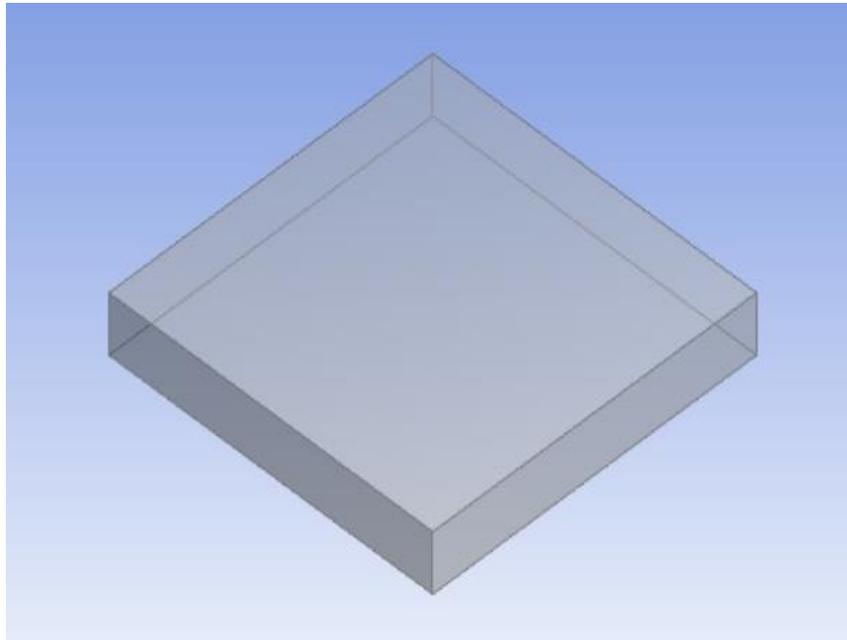

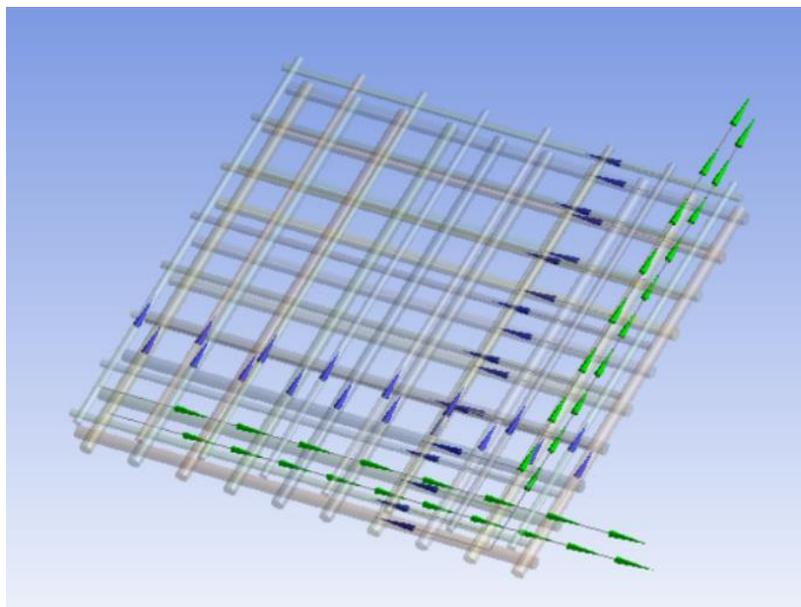Figure 5.2 Model of LWC flat slab developed in ANSYS

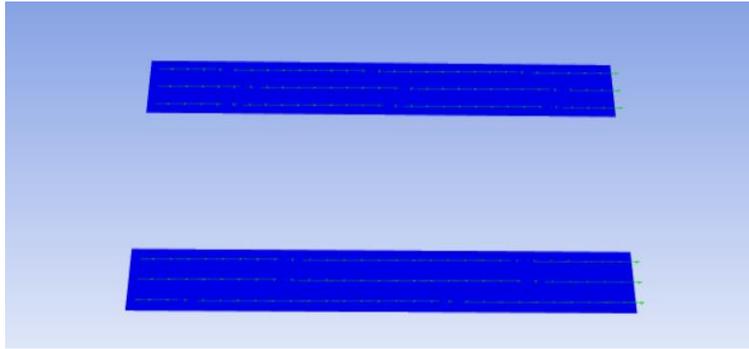Figure 5.3 Reinforcement details of the model developed ANSYS

Figure 5.4 Model of GFRP strip developed in ANSYS

5.2.1 Material Properties of Concrete

The concrete is modelled using solid domains. The material properties of concrete are shown in table 5.1.

Table 5.1 Material properties of concrete (Source said et al. (2020)

MATERIAL	PROPERTY
Lightweight concrete	Density = 16.50 kN/m^2
	Compressive strength = 25 MPa
	Young's modulus = 23500 MPa
	Poisson's ratio = .18

5.2.2 Material modelling of steel

A bilinear stress-strain curve is used to idealize the behaviour of the steel reinforcement. In the bilinear isotropic hardening process, both stress and strain change even after reaching maximum plastic deformation. Table 5.2 shows the material properties of steel.

Table 5.2 Material properties of steel (Said et al (2020)

MATERIAL	PROPERTIES
Steel	Density = 7850 kg/m^3
	Yield strength = MPa
	Ultimate strength = 580 MPa
	Poisson' ratio = 0.2

5.2.3 Material Modelling of GFRP

The lightweight concrete flat slab is strengthened using glass fibre-reinforced polymer (GFRP).

Table 5.3 The material properties of GFRP (Source A. Alhayek et al. (2019)

MATERIAL	PROPERTIES
GFRP	Density (ρ) = 2050 kg/m^3
	Young's Modulus in X direction (E1) = 36.3 MPa
	Young's Modulus in Y direction (E2) = 10.8 MPa
	Young's Modulus in Z direction (E3) = 10.8 MPa
	Poisson's Ratio XY (v12) = 0.28
	Poisson's Ratio YZ (v13) = 0.09
	Poisson's Ratio XZ (v23) = 0.28
	Shear Modulus XY (G12) = 4 GPa
	Shear Modulus YZ (G13) = GPa
	Shear Modulus XZ (G23) = 4 GPa
	Tensile X direction (Xt) = 596 MPa
	Tensile Y direction (Yt) = 55 MPa
	Tensile Z direction (Zt) = 55 MPa
	Compression in X direction (Xc) = 550 MPa
	Compression in Y direction (Yc) = 120 MPa
	Compression in Z direction (Zc) = 120 MPa
	Shear XY = 86 MPa
	Shear YZ = 44 MPa
	Shear XZ = 86 MPa

5.3 LOADING AND BOUNDARY CONDITION

Newton-Rapson equilibrium iterations were used for nonlinear analysis. Through the centre of the flat slab's top (150x150mm) area, a displacement-controlled incremental loading was applied in the Z direction. And the reaction force and corresponding total deformation were calculated at the prescribed load. The support is provided 75 mm from the slab's edge at the bottom. Movement is restricted against the X and Z axes on one side of the slab, and fixed

support is provided on the other. The LWC Loading and boundary conditions of the slab are figure 5.5.
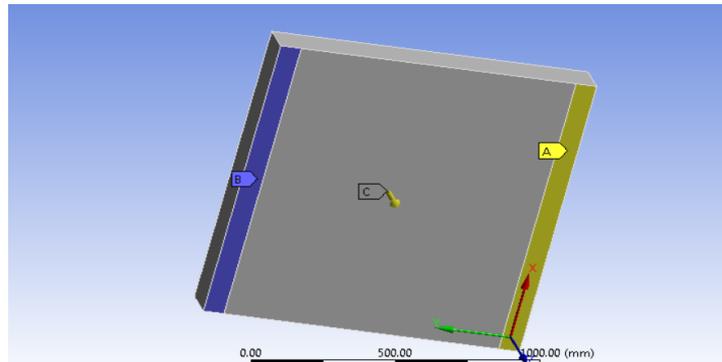

Figure 5.5 Loading and boundary condition of the slab

5.4 MESH ARRANGEMENT

Meshing is one of the important parts of the engineering simulation process because it divides complex geometry into elements that can be used to discretize a domain. It can make a substantial impact on the simulation's accuracy and the resources required to perform the simulation. The basis of engineering simulations is improving mesh since it affects the simulations' accuracy, convergence, and speed. A mesh size of 30 mm is utilised for this study. In figure 5.6, the slab mesh model is displayed.
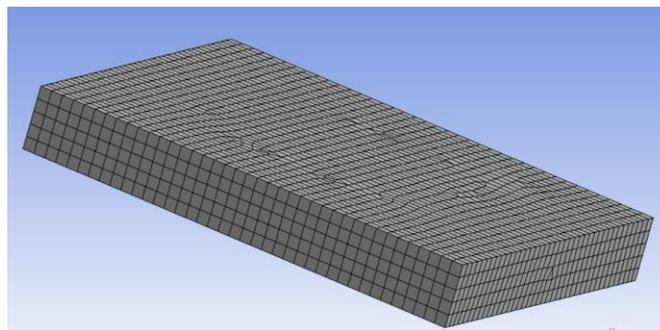

Figure 5.6 Meshed model of LWC slab

CHAPTER 6

RESULTS & DISCUSSIONS

6.1 GENERAL

The numerical analysis on LWC flat slab strengthened with GFRP strip is conducted to study the improvement of punching shear capacity of the strengthened slab as compared to the control slab. The effect of parameters such as the GFRP strip configuration, width, location, and orientation is studied and discussed in the following sections. The deformed shape of the slab and the reinforcements are shown in figure 6.1 and figure 6.2 respectively.
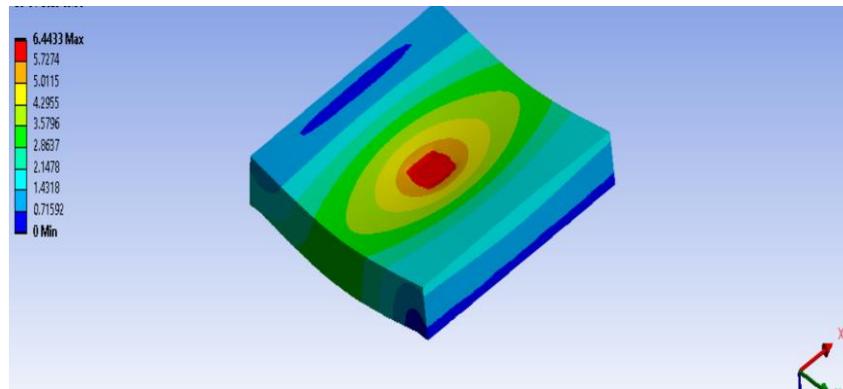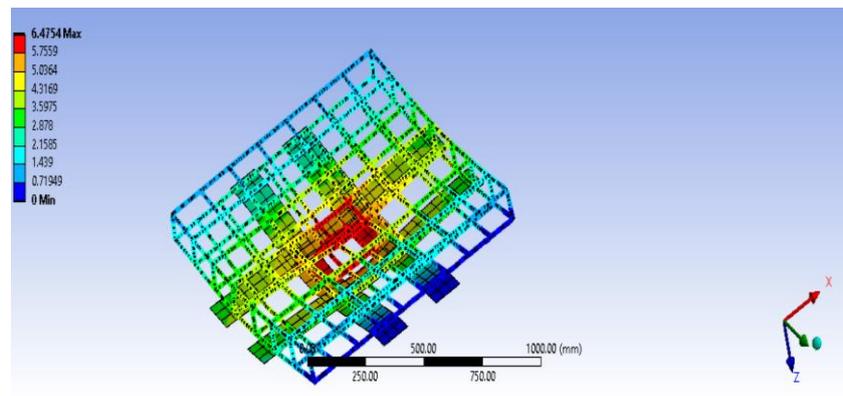

Figure 6.1 Deformed shape of LWC slab

Figure 6.2 Deformed shape of reinforcement and GFRP strip

6.2 EFFECT OF STRENGTHENING CONFIGURATION OF GFRP STRIP

To investigate the effect of GFRP strip orientation in the punching shear performance of LWC flat slab under concentrated load. Figure 6.3 illustrates the fibre orientation in the GFRP strip.

Figure 6.4 displays the load-displacement curve for control slabs and a slab strengthened with GFRP strip in various orientations. The control slab is the LWC flat slab that is not strengthened. For slabs S-2-O-O-0°, S-4-O-O, and S-8-O-A-125, the slabs were strengthened in an orthogonal manner at offset distances of 2, 4, and 8 strips, respectively, from the loading surface. The slab was strengthened in S-4-D-O in a diagonal direction at an offset distance from the loading surface. The load-deformation curve for the LWC slab that has been strengthened with a GFRP strip and the normal LWC slab is shown in the figure. It can be concluded that the punching shear capacity of slabs is increasing when increasing the number of layers and also providing the strips in the diagonal direction. Strengthened LWC slabs have a higher punching shear capacity than normal LWC slabs. Comparing strengthened slabs S-2-O-O-0°, S-4-O-O, S-4-D-O, and S-8-O-A-125 to normal LWC slabs, the improvements in punching shear capacity were 30%, 36.9%, 39.4%, and 40.2%, respectively.

(a) S
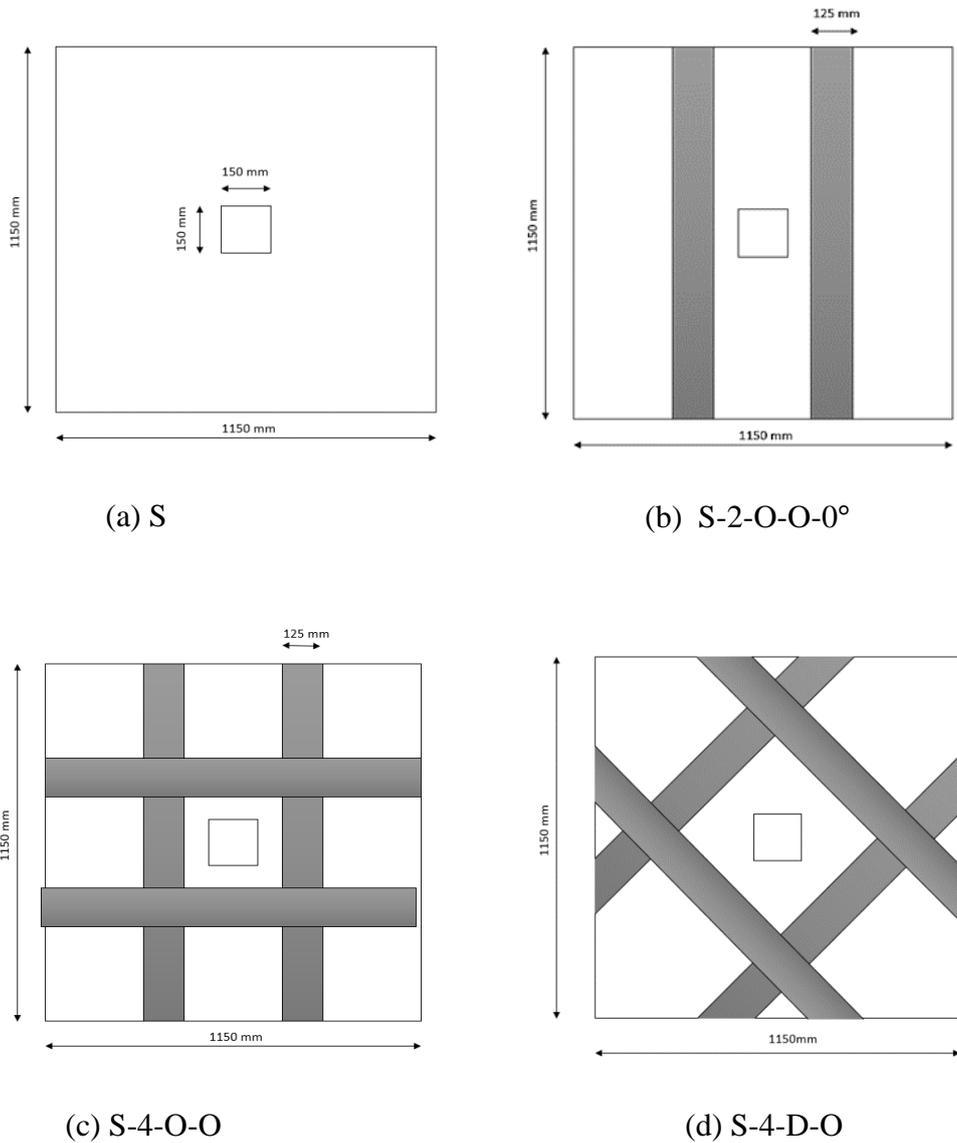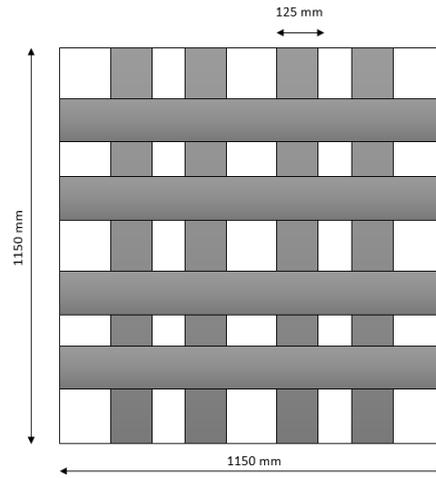
(b) S-2-O-O-0°

(c) S-4-O-O

(d) S-4-D-O

(e) S-8-O-A-125

Figure 6.3 Slab strengthening schemes slabs (a) S, (b) S-2-O-O-0°, (c) S-4-O-O, (d) S-4-D-O and (e) S-8-O-A-125
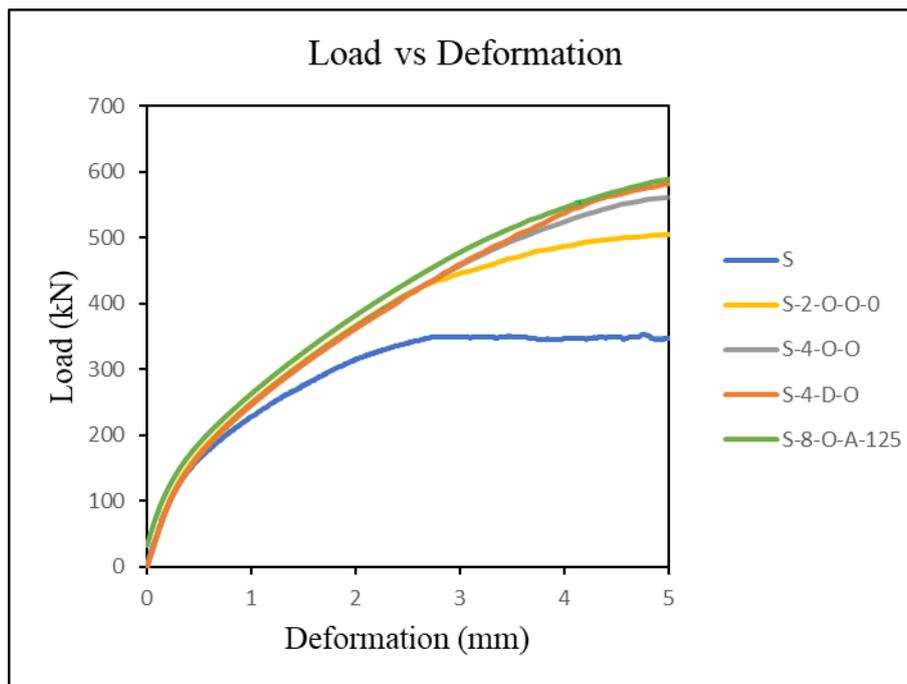

Figure 6.4 Load vs Deformation curve of slabs S, S-2-O-O-0°, S-4-O-O, S-4-D-O and S-8-O-A-125

7.3 EFFECT OF WIDTH OF GFRP STRIP

The LWC slabs were strengthened with various widths of strips in order to study the impact of strip width on punching shear performance. The configuration pattern of slabs is shown in figure 6.5. The slabs S-8-O-A-75, S-8-O-A-100 and S-8-O-A-125 are strengthened by the

strips of width 75 mm, 100 mm and 125 mm respectively. Figure 6.6 displays the load-deformation curve for each slab. Compared to the normal LWC slab, all of the strengthened slabs had a higher punching shear capability. In comparison to the standard LWC slab, the strengthened slabs S-8-O-A-75, S-8-O-A-100, and S-8-O-A-125 have improved punching shear capacities by 36.3%, 42.1%, and 40.8%, respectively. The slab with a 100 mm thickness has a higher punching shear capacity than the others, according to the results. It can be seen that the loading carrying capacity of specimens reinforced with GFRP strips increased up to a certain point and thereafter decreases.The stiffness of slab increrases as increasimg the number of strips so that its fails before subjected to much deformation. And concluded that the increasing stips doesnot increases the punching shear capacity and the cost also increases whlie providing too many strips.

(a) S-8-O-A-75   (b) S-8-O-A-100
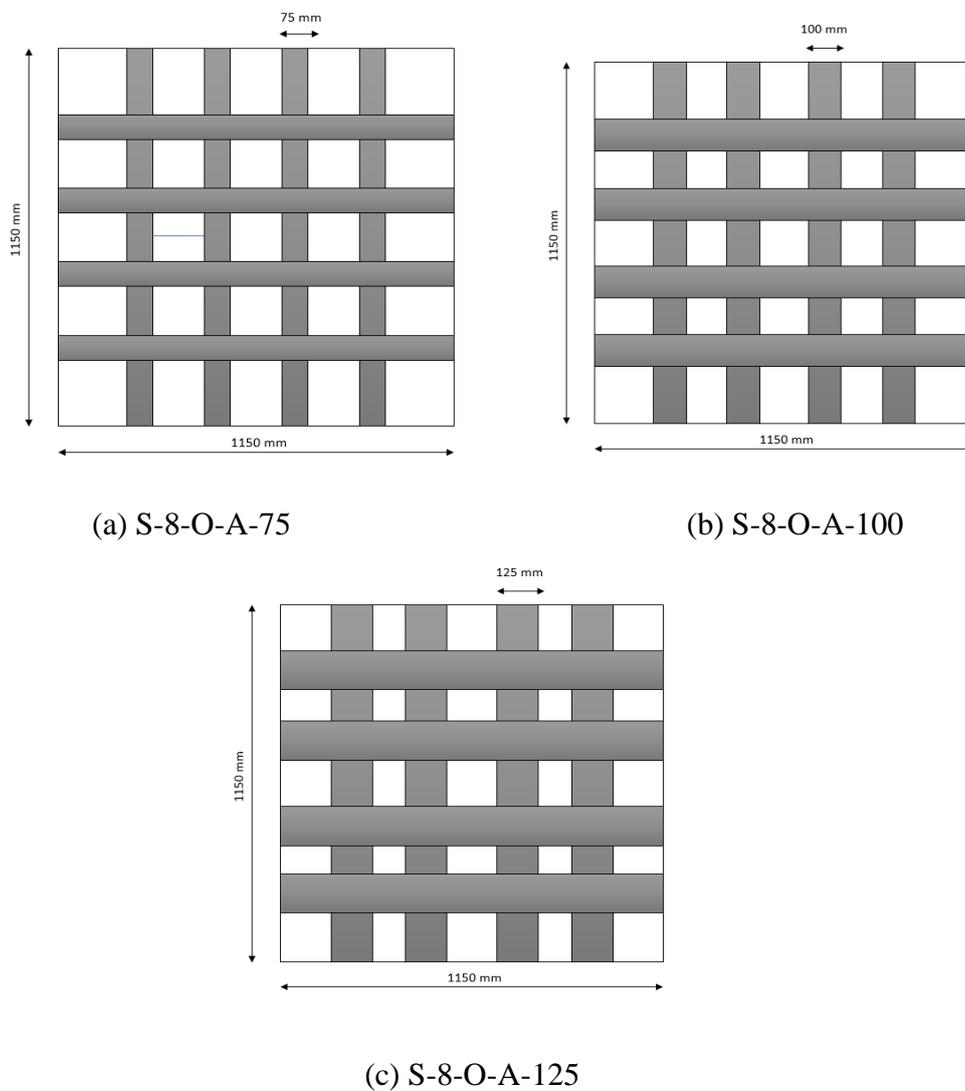

(c) S-8-O-A-125

Figure 6.5 Slab strengthening schemes of slabs (a) S-8-O-A-75, (b) S-8-O-A-100 and (c) S-8-O-A-125
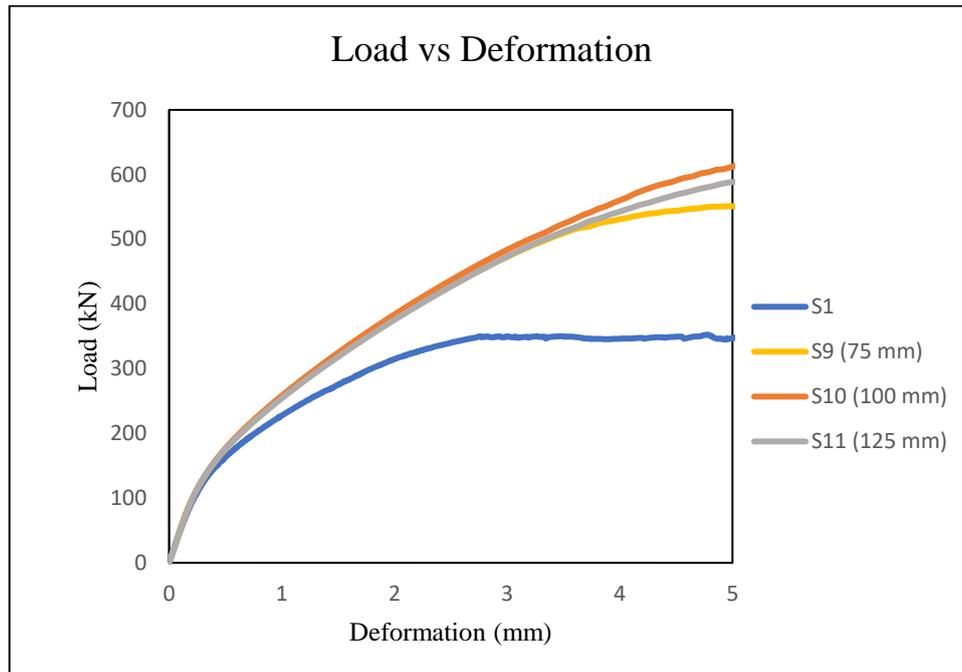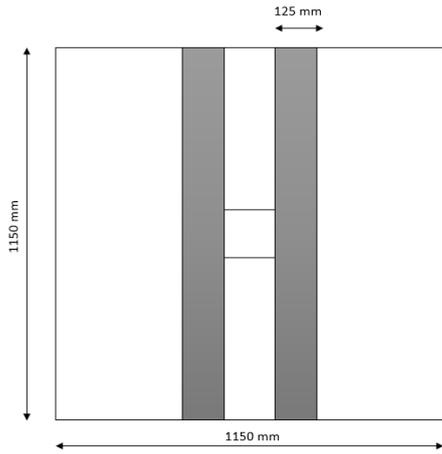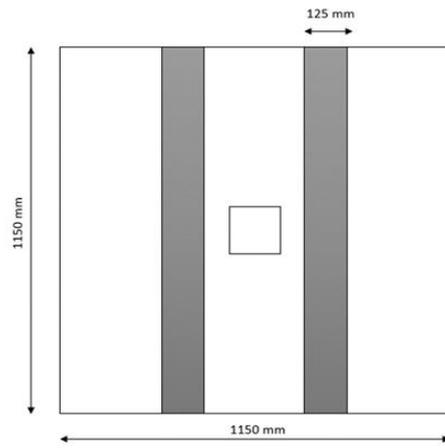
Figure 6.6 Load vs Deformation curve of slab S-8-O-A-75, S-8-O-A-100 and S-8-O-A-125

6.4 EFFECT OF LOCATION OF GFRP STRIP

To investigate the effect of the location of the GFRP strip on the punching shear performance slab was checked By placing a GFRP strip next to the loading surface and the offset distance from the loading surface was analyzed and compared to a normal LWC slab. Figure 6.7 depicts the slab strengthening schemes. The slabs S-2-O-A, S-4-O-A, and S-4-D-A were strengthened by providing strips adjacent to the loading surface. In slab S-2-O-O-0°, S-4-O-O and S-4-D-O the strips are provided at an offset distance from the loading surface. In figures 6.8, 6.9, and 6.10, the load-deformation curve of the slab strengthened under different schemes is displayed. The slabs punching shear capability is larger in slabs where the GFRP strips are offset from the loading surface than it is in slabs where they are near to the loading surface. The GFRP strips are provided in a diagonal direction at an offset distance from the loading surface giving good results as compared to the other slabs. Punching shear capacity of strengthened slabs S-2-O-A, S-2-O-O-0°, S-4-O-A, S-4-O-O, S-4-D-A, are S-4-D-O are 21.2%, 30%, 33.6%, 36.5%, 35.8% and 39.8% enhanced as compared to the normal LWC slab.

(a) S-2-O-A   (b) S-2-O-O-0°
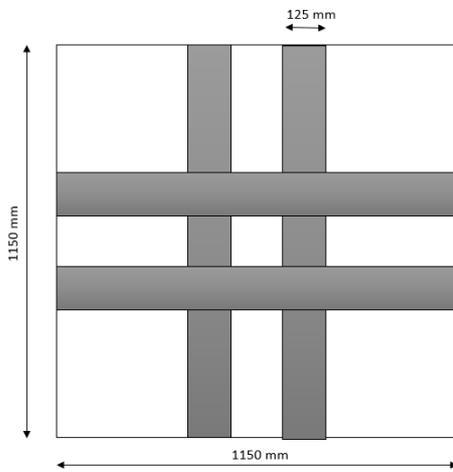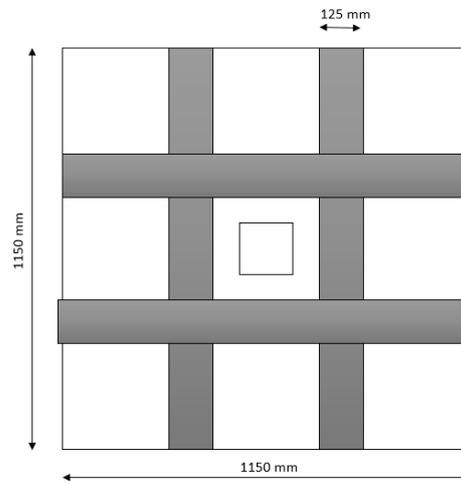
(c) S-4-O-A   (d) S-4-O-O
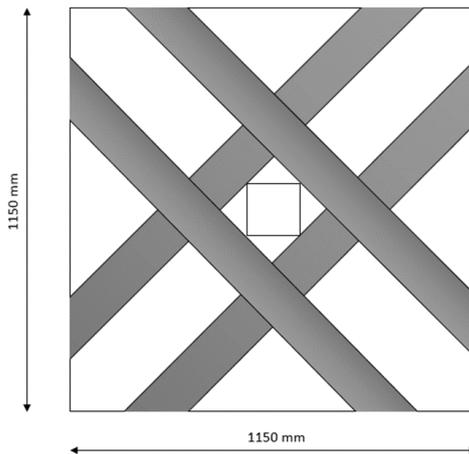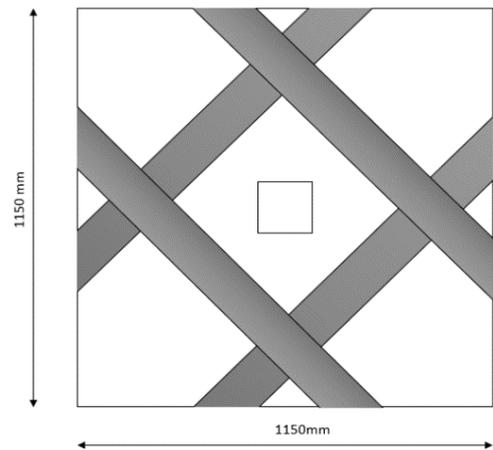
(e) S-4-D-A   (f) S-4-D-O

Figure 6.7 Slab strengthening schemes of slabs **(a)** S-2-O-A, **(b)** S-2-O-O-0°, (c) S-4-O-A, (d) S-4-O-O , (e) S-4-D-A and (f) S-4-D-O
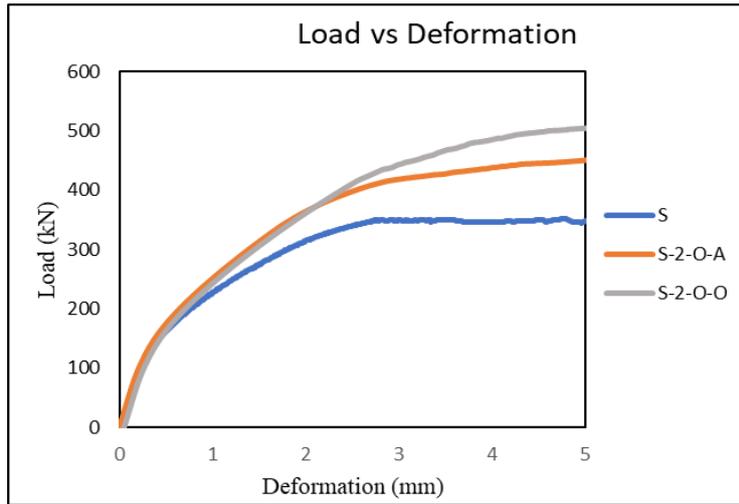
Figure 6.8 Load vs Deformation curve of slabs S-2-O-A and S-2-O-O-0°
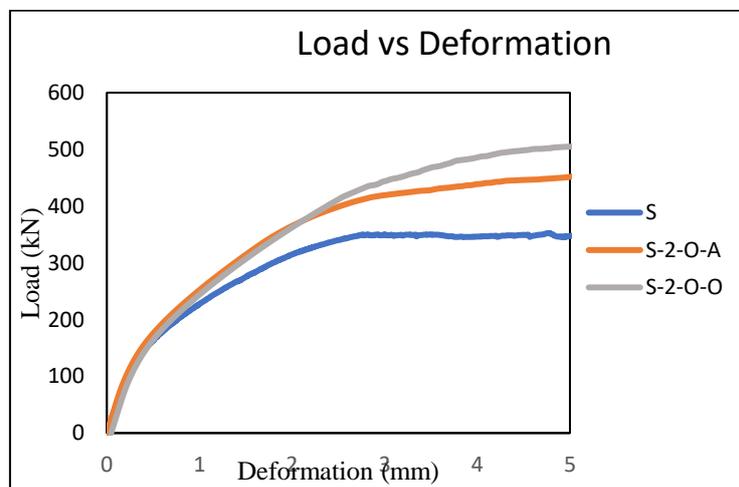
Figure 6.9 Load vs Deformation curve of slabs S-4-O-A and S-4-O-O
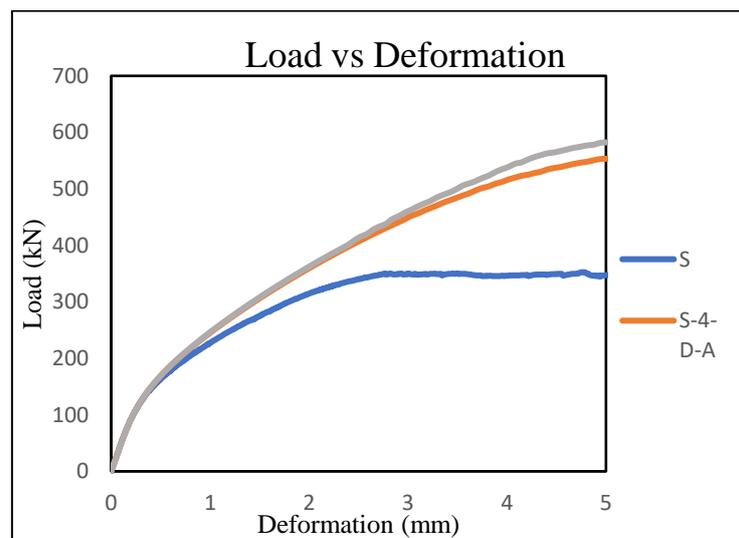
Figure 6.10 Load vs Deformation curve of slabs S-2-D-A and S-2-D-O

6.5 EFFECT OF FIBRE ORIENTATION

To investigate the effect of the fibre orientation angle in the punching shear performance of strengthened LWC slab. The strip is provided in the orientation of 0 and 45 degrees. Figure 6.11 illustrates the strips that were used to reinforce the slabs S-2-O-O -0° and S-2-O-O-45° with fibre oriented at 0 and 45 degrees, respectively. Figure 6.12 displays the load-deformation curve for specimens. S-2-O-O -0° and S-2-O-O-45° punching shear capacity slabs improve on the standard LWC slab by 30% and 29.5%, respectively. It can be concluded that the only slight variation in the result was changing the fibre orientation.

(a) S-2-O-O-0°   (b) S-4-O-O-45°

Figure 6.11 Load vs Deformation curve of slabs (a) S-2-O-O-0° and (b) S-4-O-O-45°

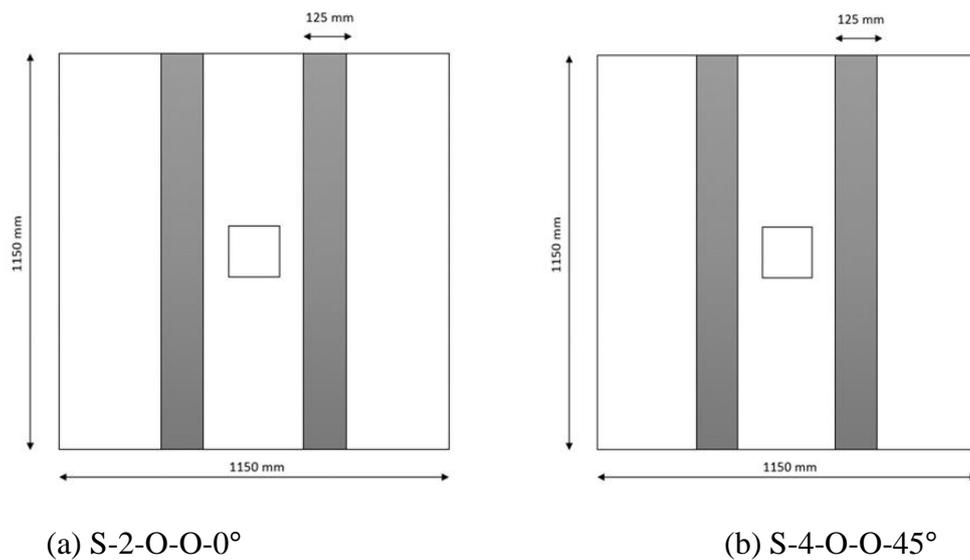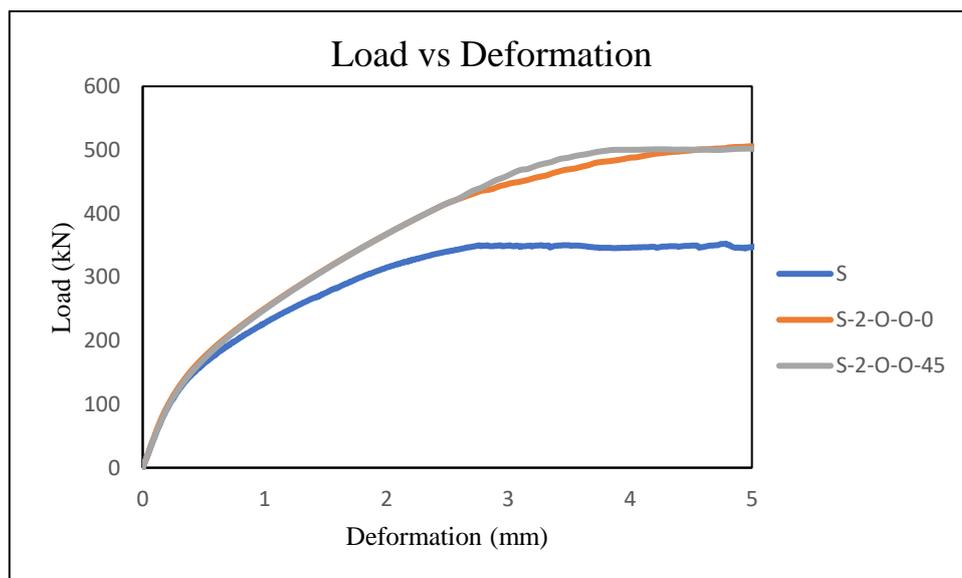Figure 6.12 Load vs Deformation curve of slabs S-2-O-O-0° and S-4-O-O-45°

6.6 COMPARISON OF THE SLABS IN TERMS OF DUCTILITY FACTOR AND ENERGY ABSORPTION

6.6.1 Ductility factor

The degree to which a material (or structure) can withstand significant deformations without failing is referred to as ductility. Ductility measures a material's ability to plastically deform without fracturing when placed under a tensile stress that exceeds its yield strength. Low ductility suggests that a material is brittle and will fracture before deforming under a tensile strain, whereas high ductility indicates that a material will be more likely to deform and not break. Structures made of reinforced concrete need to be structurally ductile in order to prevent brittle, rapid failure. In ductile structures, significant deflection ensures adequate advance notice of the structure's impending failure. The ductility factor suggested by Said et. al. (2020) is the ratio of the ultimate deformation to the deformation at the beginning of the horizontal path. The ductility factor for all slabs is shown in table 6.1. It can be concluded that the ductility factor of strengthened slabs is more than that of normal LWC slabs. Increase in ductility factor with the increasing number of strips. The slabs S-8-O-O-125 and S-8-O-O-100 showed more ductility factors. For the slabs, the strip provided near to loading face has low ductility factor than the slabs with the strip provided at an offset distance from the loading face.

Table 6.1 The ductility factor of all specimens

Specimen	Ultimate Load (kN)	Ultimate displacement (mm)	Ductility factor
S1	353	6.03	1.26
S2	448	6.1	1.29
S3	505	6.144	1.31
S4	501	6.28	1.30
S5	532	6.47	1.30
S6	560	6.48	1.31
S7	550	6.53	1.31
S8	587	6.52	1.32
S9	565	6.56	1.33
S10	610	6.58	1.34
S11	597	6.66	1.34

6.6.2 Energy absorption

Energy absorption represents the capability of a material to undergo deformation before failure and it is also known as the slab's toughness capability. Energy absorption can be defined as the area under the horizontal path. Energy absorption plays a very important role in protecting buildings from collapse during an earthquake. Energy absorption in concrete structures include energy dissipated by steel reinforcements, energy dissipated during crack development, and friction between crack surfaces. As a result, they are the ones who absorb energy and reduce the effects of seismic forces on the structure. Certain structural members can withstand large deformations. Table 6.2 displays the total energy absorption of all slab models.

Table 6.2 Energy absorption of specimens

Specimen	Energy absorption (kN. mm)
S1	1877
S2	1977
S3	2526
S4	2463
S5	2599
S6	2699
S7	2651
S8	2740
S9	2764
S10	2830
S11	2887

All of the strengthened LWC slabs outperformed the standard normal LWC slab in terms of energy absorption, demonstrating that the rehabilitation strategy is effective. From the results, it can be concluded that the energy absorption capacity of the strengthened slabs is higher than that of the control slab. The energy absorption increases with an increasing number of layers. In slabs, the strip provided in the diagonal direction has more punching shear capacity than the slab strip provided in the orthogonal direction. It was determined that strengthening slabs using GFRP dissipate more energy than the control when subjected to large lateral displacements of other structural members, ensuring the structure's safety.

CHAPTER 7

CONCLUSION

Flat slab structural systems are frequently used in various construction scenarios, such as multistorey buildings, bridges and parking garages for their great economical superiority and ease of construction. A flat slab is a RC slab that is supported directly by a concrete column without the use of a beam. The slab-column connection problem may be effectively solved by reducing the weight of RC slabs. The introduction of the reinforced lightweight concrete flat slab is helpful in decreasing the weight of the RC slabs which thereby solves the slab column connection problem. Punching shear is a failure mechanism in structural members like slabs and foundations under the action concentrated force and it occurs at column support points in flat slabs. Fibre-reinforced polymer (FRP), is an alternative to steel reinforcement and presently, glass fibres are identified as the most adaptable manufacturing materials among others. The numerical model has been validated with the published results based on the experiment conducted by Said et. al. (2020). From the analysis, for strengthened slab displayed an enhancement in the punching shear capacity for all specimens compared with the control specimens without shear reinforcement. It is possible to increase the ultimate load-carrying capacity by 30% as compared to the control slab. From the comparison of different configurations of GFRP strips, the GFRP strips provided in a diagonal direction show more load-carrying capacity than the strip provided in the orthogonal direction. By adding more layers up to a particular limit, there is an increase in the ultimate load-carrying capacity of the slab. From the comparison of the width of the strip (75mm, 100mm and 125mm) the strip of a width of 100 mm gives more load-carrying capacity so that, the increasing the width of the strip increases the load-carrying capacity at a particular limit. The strip provided is at an offset distance from the loading surface of the slabs showing more punching shear capacity than the slab having a strip provided adjacent to the loading surface. The change in orientation of fibre in a specimen does not have much effect on the load-carrying capacity. Ductility factor of all strengthened specimens enhanced as compared to the control slab. The energy absorption is high when increasing the number of layers. From the analysis, the strip provided in a diagonal direction at an offset distance is the effective strengthening in terms of punching shear capacity, ductility, energy absorption and also considering the economy. Overall, the GFRP is an effective material to strengthen the LWC slab against punching shear as its load-carrying capacity, ductility factor, and energy absorption are increased.

REFERENCES

- Akil, H. M., Santulli, C., Sarasini, F., Tirillò, J., & Valente, T. (2014). Environmental effects on the mechanical behaviour of pultruded jute/glass fibre-reinforced polyester hybrid composites. *Composites Science and Technology*, *94*, 62-70.

- Amiri, S., & Talaeitaba, S. B. (2020, August). Punching shear strengthening of flat slabs with EBROG and EBRIG–FRP strips. In *Structures* (Vol. 26, pp. 139-155). Elsevier.

- Caratelli, A., Imperatore, S., Meda, A., & Rinaldi, Z. (2016). Punching shear behavior of lightweight fiber reinforced concrete slabs. *Composites Part B: Engineering*, *99*, 257-265.

- Cui, H. Z., Lo, T. Y., Memon, S. A., & Xu, W. (2012). Effect of lightweight aggregates on the mechanical properties and brittleness of lightweight aggregate concrete. *Construction and Building materials*, *35*, 149-158.

- Fava, G., Carvelli, V., & Pisani, M. A. (2016). Remarks on bond of GFRP rebars and concrete. *Composites Part B: Engineering*, *93*, 210-220.

- Genikomsou, A. S., & Polak, M. A. (2016). Finite-element analysis of reinforced concrete slabs with punching shear reinforcement. *Journal of Structural Engineering*, *142*(12), 04016129.

- Hassan, Mohamed, Ehab A. Ahmed, and Brahim Benmokrane. "Punching shear behavior of two-way slabs reinforced with FRP shear reinforcement." *Journal of Composites for Construction* 19.1 (2015): 04014030.

- Jasim, A. H., & Ammash, H. K. (2021, May). Effect of using column capital on the punching shear strength of flat slab-edge column connection under eccentric loading. In *Journal of Physics: Conference Series* (Vol. 1895, No. 1, p. 012060). IOP Publishing.

- Kim, H. K., Jeon, J. H., & Lee, H. K. (2012). Workability, and mechanical, acoustic and thermal properties of lightweight aggregate concrete with a high volume of entrained air. *Construction and Building Materials*, *29*, 193-200.

- Lapi, M., Ramos, A. P., & Orlando, M. (2019). Flat slab strengthening techniques against punching-shear. *Engineering Structures*, *180*, 160-180.

- Loganaganandan, M., Murali, G., Salaimanimagudam, M. P., Haridharan, M. K., & Karthikeyan, K. (2021). Experimental study on GFRP strips strengthened new two stage concrete slabs under falling mass collisions. *KSCE Journal of Civil Engineering*, *25*(1), 235-244.

- Mabrouk, R. T., Bakr, A., & Abdalla, H. (2017). Effect of flexural and shear reinforcement on the punching behavior of reinforced concrete flat slabs. *Alexandria Engineering Journal*, *56*(4), 591-599.

- Madkour, H., Maher, M., & Ali, O. (2022). Finite element analysis for interior slab-column connections reinforced with GFRP bars using damage plasticity model. *Journal of Building Engineering*, *48*, 104013.

- Marques, M. G., Liberati, E. A., Pimentel, M. J., de Souza, R. A., & Trautwein, L. M. (2020, October). Nonlinear finite element analysis (NLFEA) of reinforced concrete flat slabs with holes. In *Structures* (Vol. 27, pp. 1-11). Elsevier.

- Meisami, M. H., Mostofinejad, D., & Nakamura, H. (2015). Strengthening of flat slabs with FRP fan for punching shear. *Composite structures*, *119*, 305-314.

- Mohamed, O. A., Kewalramani, M., & Khattab, R. (2020). Fiber reinforced polymer laminates for strengthening of rc slabs against punching shear: A review. *Polymers*, *12*(3), 685.

- Mostofinejad, D., Jafarian, N., Naderi, A., Mostofinejad, A., & Salehi, M. (2020, June). Effects of openings on the punching shear strength of reinforced concrete slabs. In *Structures* (Vol. 25, pp. 760-773).

- Neamah, Z. A., & Al-Ramahee, M. A. (2021, February). Punching shear strength of flat slab strengthened with reinforced concrete column capital under bi-axial loading. In *IOP Conference Series: Materials Science and Engineering* (Vol. 1067, No. 1, p. 012005). IOP Publishing.

- Ou, Y., & Zhu, D. (2015). Tensile behavior of glass fiber reinforced composite at different strain rates and temperatures. *Construction and Building Materials*, *96*, 648-656.

- Panigrahi, A. K., Biswal, K. C., & Barik, M. R. (2014). Strengthening of shear deficient RC T-beams with externally bonded GFRP sheets. *Construction and Building Materials*, *57*, 81-91.

- Parvin, A., & Syed Shah, T. (2016). Fiber reinforced polymer strengthening of structures by near-surface mounting method. *Polymers*, *8*(8), 298.

- Qian, K., & Li, B. (2013). Experimental study of drop-panel effects on response of reinforced concrete flat slabs after loss of corner column. *ACI Structural Journal*, *110*(2), 319.

- Rajak, D. K., Wagh, P. H., & Linul, E. (2021). Manufacturing technologies of carbon/glass fiber-reinforced polymer composites and their properties: A review. *Polymers*, *13*(21), 3721.

- Sahranavard, S., Jahangir, H., & Kazemi, H. H. (2022, November). An experimental and numerical investigation of RC slabs externally strengthened by perforated steel plates. In *Structures* (Vol. 45, pp. 1239-1252). Elsevier.

- Said, M., Adam, M. A., Arafa, A. E., & Moatasem, A. (2020). Improvement of punching shear strength of reinforced lightweight concrete flat slab using different strengthening techniques. *Journal of Building Engineering*, *32*, 101749

- Sanginabadi, K., Yazdani, A., Mostofinejad, D., & Czaderski, C. (2022). Bond behavior of FRP composites attached to concrete using EBROG method: A state-of-the-art review. *Composite Structures*, 116060.

- Shatarat, N., & Salman, D. (2022). Investigation of punching shear behavior of flat slabs with different types and arrangements of shear reinforcement. *Case Studies in Construction Materials*, *16*, e01028.

- Soltani, H., Khaloo, A., & Sadraie, H. (2020). Dynamic performance enhancement of RC slabs by steel fibers vs. externally bonded GFRP sheets under impact loading. *Engineering Structures*, *213*, 110539.

- Soudki, K., El-Sayed, A. K., & Vanzwol, T. (2012). Strengthening of concrete slab-column connections using CFRP strips. *Journal of King Saud University-Engineering Sciences*, *24*(1), 25-33.

- Tetta, Z. C., Koutas, L. N., & Bournas, D. A. (2015). Textile-reinforced mortar (TRM) versus fiber-reinforced polymers (FRP) in shear strengthening of concrete beams. *Composites Part B: Engineering*, *77*, 338-348.

- Torabian, A., Isufi, B., Mostofinejad, D., & Ramos, A. P. (2020). Flexural strengthening of flat slabs with FRP composites using EBR and EBROG methods. *Engineering Structures*, *211*, 110483.

- Urban, T., Gołdyn, M., Krawczyk, Ł., & Sowa, Ł. (2019). Experimental investigations on punching shear of lightweight aggregate concrete flat slabs. *Engineering Structures*, *197*, 109371.

- Veljkovic, A., Carvelli, V., Haffke, M. M., & Pahn, M. (2017). Concrete cover effect on the bond of GFRP bar and concrete under static loading. *Composites Part B: Engineering*, *124*, 40-53.

- Wiater, A., & Siwowski, T. (2020). Serviceability and ultimate behaviour of GFRP reinforced lightweight concrete slabs: Experimental test versus code prediction. *Composite Structures*, *239*, 112020.

- Yan, F., Lin, Z., & Yang, M. (2016). Bond mechanism and bond strength of GFRP bars to concrete: A review. *Composites Part B: Engineering*, *98*, 56-69.

- Yankelevsky, D. Z., Karinski, Y. S., Brodsky, A., & Feldgun, V. R. (2021). Dynamic punching shear of impacting RC flat slabs with drop panels. *Engineering Failure Analysis*, *129*, 105682

- Zemour, N., Asadian, A., Ahmed, E. A., Khayat, K. H., & Benmokrane, B. (2018). Experimental study on the bond behavior of GFRP bars in normal and self-consolidating concrete. *Construction and Building Materials*, *189*, 869-881.