BEHAVIORAL STUDY OF REINFORCED CONCRETE SLAB STRENGTHENED WITH EXTERNALLY BONDED FIBRE REINFORCED POLYMER LAMINATES USING FINITE ELEMENT METHOD

A thesis submitted towards partial fulfillment of the requirements for the degree of

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submitted by

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Declaration of Originality and Compliance of Academic Ethics

I hereby declare that this thesis contains literature survey and original research work by the undersigned candidate, as part of my **Master of Engineering** in **Civil Engineering (Structural Engineering)** in the Faculty of Engineering and Technology, Jadavpur University during academic session (regt. no. 163462) of 2022-23.

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This is to certify that the thesis entitled "**Behavioral Study of Reinforced Concrete Slab Strengthened with Externally Bonded Fiber Reinforced Polymer Laminates Using Finite Element Method**" is a bonafide work carried out by **Mr. Avik Samaddar** under our supervision and guidance for partial fulfillment of the requirement for the Post Graduate Degree of Master of Engineering in Civil Engineering (Structural Engineering) during the academic session 2022-2023.

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ABSTRACT

The present work is a study on the behavior of reinforced concrete slab strengthened with Externally Bonded Fibre Reinforced Polymer (EBFRP) following nonlinear finite element approach using ANSYS software. Nonlinear material properties of concrete, steel and FRP made of glass Fibre are incorporated in the finite element model. Simply supported slabs are analyzed under monotonically increasing uniformly distributed external mechanical load till its failure. The load displacement response of strengthened slab models are plotted and compared with the same for un-strengthened slab to assess the extents of enhancements in the ultimate load carrying capacity and stiffness of the slabs due to the attachment of FRP laminates with the concrete surface in different mode of arrangement. The load displacement response and the cracking profile of individual models are also compared among themselves to find the most efficient way of strengthening of RC slab with FRP laminates. Further the percentage increase in the load carrying capacity due to attachment of FRP have been plotted against the proportion of surface area of slab and a numerical model in the form of an equation is suggested to predict the increase in the ultimate load carrying capacity based on the proportion of surface area of slab covered with FRP.

CONTENTS

CHAPTER 1. INTRODUCTION

Reinforced concrete slab is the most basic structural component in a RC frame structure. Though it mainly carries the transverse load, under lateral forces like wind and seismic actions it may be subjected to axial forces in addition to bending moment and shear forces. Due to different reasons the load carrying capacity of RC slab reduces with time. Alternatively, the its capacity may need to be increased due to several reasons such as enhanced external loads due to the change in usage, change in codal provisions, making it resistant to higher seismic forces etc. The strengthening of these RC slabs are needed to take into account the above mentioned requirements.

Out of different conventional strengthening methodologies, use of Fibre Reinforced Polymer (FRP) laminates is a technically advantageous one and is widely used for the last few decades throughout the world. The material of FRP may vary from Carbon, Glass, Aramid to Basalt. The procedure of strengthening may vary based on the type of RC components, nature of performance that are to be enhanced, support conditions, the loads that will be acting over the structural components etc. It is found that the load carrying capacity of the structural component can be enhanced by attaching FRP sheets or laminates over the concrete surface using epoxy resin.

1.1. What is FRP ?

Fiber-Reinforced Polymer (FRP) is a composite material made up of a polymer matrix reinforced with fibers. The fibers are typically strong and stiff materials such as glass, carbon, or aramid fibers, while the polymer matrix is a plastic material that surrounds and binds the fibers together. FRP materials are used in various industries and applications due to their high strength-to-weight ratio, corrosion resistance, and versatility.

The combination of the strong fibers and the polymer matrix results in a material that can exhibit enhanced mechanical properties compared to traditional materials like steel or concrete. FRP composites are often used in construction, aerospace, automotive, marine, and infrastructure projects, among others. They can be used to strengthen existing structures, replace traditional materials, or create new designs that take advantage of their unique properties. Some common types of FRP include:

- **Fiber-Reinforced Plastic (FRP):** This is a general term for any composite material where fibers are embedded in a polymer matrix. Fiberglass, which uses glass fibers, is a well-known example of FRP.
- **Carbon Fiber-Reinforced Polymer (CFRP):** This type of FRP uses carbon fibers as the reinforcing material. CFRP is known for its high strength, low weight, and excellent stiffness, making it popular in applications like aerospace and high-performance sports equipment.
- **Glass Fiber-Reinforced Polymer (GFRP):** GFRP uses glass fibers as the reinforcement. It is commonly used in construction for reinforcing concrete structures or creating lightweight architectural elements.

- **Aramid Fiber-Reinforced Polymer (AFRP):** Aramid fibers, such as Kevlar, are used in AFRP composites. These materials are known for their exceptional impact resistance and are often used in applications requiring protection against high-velocity impacts, like bulletproof vests and armor.

FRP composites offer numerous advantages, including high strength-to-weight ratios, resistance to corrosion, electromagnetic neutrality, and design flexibility. However, they also have some limitations and challenges, such as susceptibility to UV degradation, difficulty in joining or repairing, and relatively high manufacturing costs. Overall, FRP materials have revolutionized many industries by providing innovative solutions to various engineering and design challenges.

FRP-strengthened concrete refers to the process of using Fiber-Reinforced Polymer (FRP) materials to enhance the structural performance of concrete structures. This technique is commonly employed to increase the load-carrying capacity, flexural or shear strength, and overall durability of existing concrete elements that may be suffering from deterioration, structural deficiencies, or changes in usage requirements.

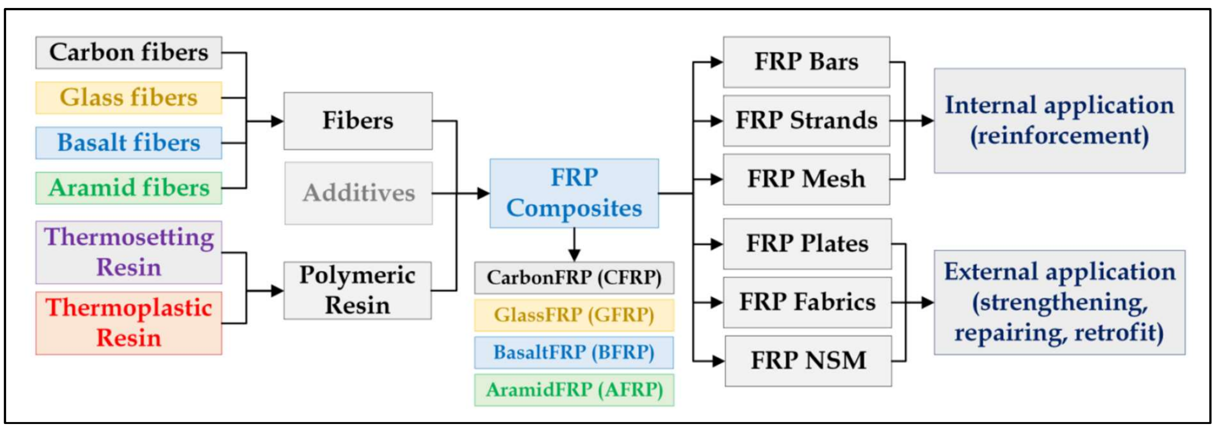


Fig. 1. Types of FRP types according to their composition and usage

1.2. FRP strengthened concrete

The process involves applying FRP sheets, strips, or bars onto the surface of the concrete element or embedding them within the concrete itself. The FRP material acts as an external reinforcement to augment the structural properties of the concrete. The primary types of FRP-strengthening techniques include:

FRP External Bonding: In this method, FRP sheets or strips are bonded to the external surface of the concrete structure using epoxy adhesive. This increases the concrete's flexural and shear capacity and can also enhance its confinement and durability.

FRP Near-Surface-Mounted (NSM) Reinforcement: With this technique, grooves are cut into the concrete surface, and FRP bars or strips are then inserted into the grooves and secured using epoxy adhesive. This approach minimizes the impact on aesthetics while providing internal reinforcement.

FRP Wet Layup: Wet layup involves saturating FRP fabric with epoxy resin and then applying it directly onto the concrete surface. This method allows for flexibility in adapting to complex shapes and irregularities.

FRP Precast Elements: In some cases, precast FRP elements such as rods or U-shaped strips are cast into the concrete element during its construction to provide enhanced reinforcement from the inside.

1.2.1. Advantages of FRP-strengthened concrete include:

- Increased Load-Carrying Capacity: FRP materials can significantly increase the load-carrying capacity of the concrete element, allowing it to support greater loads.
- Improved Flexural and Shear Strength: FRP reinforcement can enhance the concrete's ability to resist bending and shear forces, thereby preventing or delaying structural failure.
- Corrosion Resistance: Unlike traditional steel reinforcement, FRP does not corrode, making it an ideal solution for structures exposed to corrosive environments.
- Rapid Installation: FRP-strengthening techniques often require minimal disruption to the structure and can be installed relatively quickly compared to traditional methods.
- Reduced Dead Load: FRP is lightweight compared to traditional steel reinforcement, so it adds less dead load to the structure.

However, it's important to note that the success of FRP-strengthening projects depends on proper design, material selection, surface preparation, and installation. Inadequate installation or improper design can lead to premature debonding or other issues. Therefore, these projects should be carried out by experienced professionals following industry guidelines and standards.

1.2.2. Disadvantages of FRP strengthened concrete

While Fibre-Reinforced Polymer (FRP) strengthening offers numerous advantages, there are also some disadvantages and challenges associated with its use in concrete structures. Here are some of the key disadvantages:

- **UV Degradation and Environmental Exposure:** Many types of FRP materials are sensitive to ultraviolet (UV) radiation and environmental exposure. Over time, prolonged exposure to sunlight can degrade the polymer matrix and weaken the bond between the FRP and the concrete. This is particularly problematic for externally bonded FRP systems that are exposed to outdoor conditions.
- **Durability Concerns:** While FRP materials themselves are corrosion-resistant, the long-term durability of FRP-strengthened concrete structures can be affected by factors such as moisture ingress, temperature fluctuations, and chemical exposure. Proper design and protection measures are required to ensure the longevity of the strengthening system.
- **Debonding:** Adequate bond between the FRP and the concrete surface is crucial for effective strengthening. Improper surface preparation or bonding can lead to premature debonding, where the FRP peels away from the concrete. This can result in reduced effectiveness and even structural instability.

- **Installation Challenges:** Proper installation of FRP systems requires a high level of skill and expertise. Improper installation can lead to reduced effectiveness and potentially compromise the structural integrity of the concrete element.
- **Fire Performance:** Most polymer matrices used in FRP materials are susceptible to fire, which can lead to rapid degradation of the material's strength and structural integrity. Fire protection measures may need to be implemented to ensure adequate fire performance.
- **High Initial Costs:** FRP materials can be more expensive than traditional materials like steel reinforcement. The initial cost of materials and installation may be higher, especially when considering the need for specialized labor and equipment.
- **Limited Standards and Guidelines:** While standards and guidelines for FRP-strengthened concrete have been developed, they may not cover all potential applications or scenarios. Designers and engineers need to carefully consider project-specific conditions and requirements.
- **Anisotropic Behaviour:** FRP materials are typically anisotropic, meaning their mechanical properties can vary based on the direction of the fibers. This can complicate the design process and require careful consideration of load distribution and material behaviour.
- **Long-Term Behaviour and Aging:** The long-term behavior of FRP-strengthened structures, especially with respect to aging and material degradation, is still an area of ongoing research. Understanding how FRP materials age and interact with concrete over time is important for predicting the long-term performance of strengthened structures.

Despite these disadvantages, FRP-strengthening remains a valuable tool in the field of structural engineering. Many of these challenges can be addressed through proper design, material selection, installation techniques, and ongoing maintenance. It's important for professionals to have a thorough understanding of both the benefits and limitations of FRP strengthening to make informed decisions about its application.

The researchers throughout the world have kept themselves involved in the recent past to find the most advantageous, efficient and economic alternatives in the field of strengthening of RC structural components like slab, beam, column, joints etc. These research outputs have established the fact that the extent of enhancing the load carrying capacity and the stiffness of different strengthened RC components depends on different influencing parameters such as type of FRP, Location of FRP, No. of layers and FRP orientations, Nature of epoxy used, the type of structural components and its support conditions, loading type etc. But to implement this technique widely there should be some guidelines, stipulations that will give the idea regarding different steps of strengthening needed to achieve the expected extent of enhancement of load carrying capacity. The codal standards of most of the countries do not have currently such guideline. Hence there is a need for further research in the area of strengthening of RC slab with Externally bonded FRP laminates.

It has been planned to orient the current research work to find a practically applicable relationship between the extent of strengthening and the influencing parameters like location of FRP, arrangement of FRP, surface area of slab covered by FRP which may contribute towards the goal of development of the above mentioned codal guidelines for our country.

CHAPTER 2. LITERATURE REVIEW

2.1. General

Strengthening of reinforced concrete (RC) slab using FRP laminates is being widely used by engineers and professional throughout the world for last few decades. To improve its efficiency, widen its applicability, reduce the overall cost of application the researchers have continuously kept themselves engaged in carrying out the research in this field. Lots of literatures have already been published on different aspect of the mechanisms of strengthening of RC slab, the materials to be used, assessing the performance of the strengthened slabs and different innovative ideas targeting more efficient methodology of strengthening. A brief review of the existing literature both numerical and experimental studies in the area of reinforced concrete (RC) slab strengthened with FRP is presented in this chapter. This literature review focuses on recent contributions related to retrofitting or strengthening techniques of the RCC slabs only, omitting the application of same strengthening method in the other structural components like beams, columns, beam-column joint etc, to find the gap of research in this area.

2.2. Review of previous literatures

In 2002, Ebead U. A. *et al.* [4] have carried out experimental study as well as finite element analysis of two-way slabs strengthened using FRP laminates and sheets and compared the results. The effectiveness of use of FRP against flexural deficiency of the slabs have been examined. The concrete has been considered as elastic and then elasto-plastic under compression, while Pre-cracking and post cracking behaviours of concrete are considered under tension. The tension stiffening due to the present of FRP has also been considered. Perfect bond is assumed between the concrete and reinforcing steel bars and also between concrete and the strengthening FRP material. A parametric study has also been carried out to study the impact of the strengthening material type, strengthening material area ratio, span of the slab, reinforcement ratio, and thickness of the slabs. It has been attempted by them to predict the ultimate load carrying capacity of the slabs by developing simple statistical models which may reduce the time of analysis.

In 2002, Ebead U.A. [3] have reported details on the application of a strengthening technique using steel plates and steel bolts of two-way slabs subjected to different load types. The tested square slabs with a side length of 1900 mm and with two different reinforcement ratios of 0.5 and 1.0% are applied with central load, moment, and cyclic landings. Results of 11 specimens were evaluated. A column of 250 mm square in cross section is considered as located at the slab center and extended to a distance of 850 mm above and below the slab surfaces. The strengthening steel plates are extended to twice the slab depth around the column. The results shows an increase of ultimate load by an average of a minimum of 45% and 122% for specimens subjected to central load and central load plus moment, respectively. For specimens subjected to cyclic loading, the strengthening has contributed to an increase of the horizontal cyclic drift by 76% compared with the reference (unstrengthened) specimens.

In 2003, tests are conducted by **Limam *et al.*** [10] on two two-way slabs reinforced with CFRP strips until they have failed. There is a 2.5-fold increase in the ultimate strength of the reinforced slab over the unreinforced slab. In spite of this, the unreinforced slab showed more flexibility than the strengthened slab, possibly due to the premature debonding of CFRP strips during the test. Limam *et al.*. have created an analytical model that integrates diagonal yield lines and related collapse processes.

In 2003, Mosallam A. S. *et al.* [11] have presented an experimental and analytical investigation for evaluating the ultimate response of unreinforced and reinforced concrete slabs repaired and retrofitted with fibre reinforced polymer (FRP) composite strips. A uniformly distributed pressure has been applied to several two-way large-scale slab specimens using a high-pressure water bag. Both carbon/epoxy and E- glass/epoxy composite systems have been used in this study. In predicting the behaviour of the repaired slabs, the finite element method has been used. Comparison between the experimental and the analytical results indicated the validity of the computational models in capturing the experimentally determined results for both the control and the rehabilitated slabs. For repair applications, test results indicated that both FRP systems are effective in appreciably increasing the strength of the repaired slabs to approximately five times that of the as-built slabs. For retrofitting applications, use of FRP systems are resulted in appreciable upgrade of the structural capacity of the as-built slabs up to 500% for unreinforced specimens and 200% for steel reinforced specimens.

In 2003, Ebead U.A *et al.* [5] have attempted for ACI code verification of FRP externally reinforced two-way slabs. An implementation of the ACI-318 and the ACI-440 is presented for the purpose of verification against experimental results. In the experimental work, two different types of FRP materials are evaluated; namely carbon FRP (CFRP) strips and glass FRP (GFRP) laminates. The externally reinforced or strengthened slabs have steel reinforcement ratios of 0.35% and 0.5%. Results show that the flexural capacity of two way slabs can be increased to an average of 35.5% over that of the reference (unstrengthen) specimen. An increase of the initial stiffness is achieved; however, an apparent decrease in the overall ductility is evident. In addition, an average decrease in the values of the energy absorption of about 30% is observed. The estimated ultimate load capacity using the ACI code is in an accepted level of agreement with the experimental results. It is evident that the FRP materials contributed to an increase of the capacity until the bond between the FRP material and concrete failed.

In 2004, Ebead U.A. *et al.* [6] have evaluated the extent of strengthening of two-way slabs using fibre-reinforced polymers (FRPs) namely carbon FRP strips and glass FRP laminates. It has been found that the dominating failure mode for two-way slab, flexural, or punching shear depends on the slab steel reinforcement ratio. Specimens strengthened in flexure have two steel reinforcement ratios: 0.35 and 0.5%. Results obtained by them show that the flexural capacity of two-way slabs can be increased to an average of 35.5% over that of the reference (unstrengthened) specimen. An increase of the initial stiffness can also be achieved for flexural specimens; however, an apparent decrease in the overall ductility is evident. FRP materials can be used to increase the flexural capacity of two-way slabs. However, an average decrease in the values of the energy absorption of approximately 30% for flexural strengthening specimens is observed. Specimens strengthened for punching shear have an original slab reinforcement ratio of 1.0%. A strengthening technique that combines the use of carbon FRP strips and steel bolts increases the strength of the slab by 9.0%. They have also suggested an analytical model for the analysis of FRP strengthening of two-way slabs under flexure or punching shear.

In 2005, Ebead U.A. *et al.* [7] have tried to present a tension-stiffening model that is suitable for finite element analysis (FEA) to investigate the effect of FRP strengthening on the tensile behaviour of concrete slabs. They have calibrated the finite element model based on the ultimate load carrying capacity of the two-way slabs using available experimental results of the FRP strengthened reinforced concrete slabs. The proposed tension-stiffening model is implemented into the constitutive concrete model defined in a general-purpose finite element code. The behaviour of reinforced concrete in tension is found to be significantly changed due to strengthening. An overall increase in the post-peak stiffness based on the tensile stress-strain relationship is observed. A simplified bilinear model is introduced to define the behaviour of the FRP-strengthened concrete in tension. An expression of the fracture energy density is introduced to define the area under the concrete tensile stress-strain relationship. It is shown numerically that the ultimate load capacity of two-way slab specimens is sensitive to the fracture energy density. They have distinctly identified the difference between the definitions of the tension-stiffening model of FRP-strengthened and un-strengthened concrete.

In 2005, Neale K. W. *et al.*, [12] have carried out the finite element modelling of the bond behaviour of concrete beams and slabs strengthened with externally bonded FRPs. It has been emphasized to evaluate the assessment of appropriate constitutive models for the FRP/concrete interface. The concept has been applied in the basic direct shear test, and the flexural and shear strengthening of beams and slabs. The use of non-prestressed vs. prestressed FRPs is also examined. The proposed numerical models are validated against available experimental results.

In 2005, Smith S.T. *et al.* [16] have reported that reinforced concrete beams and slabs bonded with tension face fibre reinforced polymers(FRP) are susceptible to premature failure by intermediate crack(IC) induced debonding, otherwise known as IC debonding, that originates at a flexural crack. Two key parameters needed in the determination of IC debonding are (a)The load required to initiate localised debonding near the base of flexural cracks, and (b) the length of debonded plate required to cause complete loss of load carrying capacity of the FRP-strengthened member. These two parameters are investigated in this paper using a local deformation model previously reported by the authors (Gravina and Smith 2004 and 2005). A recently published bond-slip relation for the FRP-to-concrete interface (Lu *et al.*. 2005) is used to determine the onset of debonding while the local deformation model is used to investigate the debonded plate length in FRP-strengthened RC cantilever slabs. The results are compared with Chen and Teng's (2001) effective bond length and then recommendations given.

In 2008, Belakhdar K. [2] has presented an implementation of a rational three-dimensional nonlinear finite element model for evaluating the behaviour of reinforced concrete slabs strengthened with shear bolts under transverse load. The concrete has been idealized by using eight-nodded brick elements. While both flexural reinforcement and the shear bolts have been modelled as truss elements, a perfected bond between brick elements and truss elements is assumed. The nonlinear behavior of concrete in compression is simulated by an elasto-plastic work-hardening model, and in tension a suitable post-cracking model based on tension stiffening and shear retention models are employed. The steel is simulated using an elastic-full plastic model. The validity of the theoretical formulations and the program used is verified through comparison with available experimental data, and the agreement has proven to be good. A parametric study has been also carried out to investigate the influence of the shear bolts' diameter and number of bolts' rows around the column-slab connection, on the ductility and ultimate load capacity of slabs.

In 2011, Neale K.W. *et al.* [13] have reported the nonlinear finite element modelling of reinforced concrete members externally strengthened with fibre reinforced polymers (FRPs). Modelling approaches for various applications are reviewed, including the flexural and shear strengthening of beams, as well as the FRP strengthening of two-way slabs. Two types of strengthening methods are considered; namely externally bonded and mechanically fastened FRP strengthening schemes. In all applications, special attention is paid to the implementation of appropriate constitutive models for the FRP/concrete interfaces. To obtain accurate predictions, these models must be capable of properly simulating interfacial stresses and strains, as well as characterizing possible debonding failures. The performance of the various numerical models is assessed through comparisons with appropriate experimental data. It is shown that, with adequate interface models, the numerical predictions can compare very well with experimental measurements in terms of ultimate load carrying capacities, load-deflection relationships and failure modes. The numerical analyses are shown to provide useful insight into phenomena that are difficult to obtain experimentally (e.g., interfacial stress distributions and interfacial slip profiles).

In 2013, Anil *et al.* [1] have conducted tests on 12 FRP-strengthened reinforced concrete slabs. It is observed from these testing that the unstrengthened slab's load bearing capacity and stiffness increased by an average of 1.16-1.48 and 1.05-1.22, respectively. Because of the high elasticity of CFRP material, Anil and colleagues have found that reinforced slabs have a significant drop in energy dissipation capacity and ductility ratio.

In 2014, Fathelbab F. A. *et al.* [8] have studied analytically on the strengthening of a reinforced concrete bridge slabs due to excessive loads, using externally bonded FRP sheets technique. A commercial finite element program ANSYS has been used to perform a structural linear and non-linear analysis for strengthened slab models using several schemes of FRP sheets. A parametric study has been performed to evaluate analytically the effect of changing both FRP stiffness and FRP schemes in strengthening RC slabs. Comparing the results with control slab (reinforced concrete slab without strengthening) it is obvious that attaching FRP sheets to the RC slab increases its capacity and enhances the ductility or toughness. This paper represents the ANSYS computer program which is used in the analysis of different mechanical and structural applications based on the finite element modeling techniques. SOLID65 element is used to model the plain concrete material, since it has a capability of both cracking in tension and crushing in compression, SOLID65 element is defined by 8 nodes with three degrees of freedom at each node; translations in the nodal x, y, and z directions. The element material is assumed initially isotropic. The most important aspect of this element is the treatment of nonlinear material properties, where concrete is capable of directional cracking and crushing besides incorporating plastic and creep behavior.

In 2014, Gawas S. *et al.* [9] have carried out finite element analysis of RCC slab models. The study is based on the fact that stress and displacement variation depends on boundary conditions of slab. Present study is aimed to know the variation of displacement, stresses, in slab with different boundary conditions. Non-Linear static analysis is carried out using ANSYS 10 Software. Load on slab is calculated as per IS 875 part I for dead load and part II for live load. Parameter considered is to study the effect of opening in slab on stress and displacement. The study shows that displacement is highest in slab having simple support on all sides and stresses are least in same slab along the edges. Also slab with fixed support on all sides shows least displacement and highest stresses along the edges of the slab.

In 2016, **Tanu at al** [17] have analysed two-way slab having size of 450 mm*450mm*40 mm and reported the results. The reinforcing bars having diameter 6 mm are provided at 75 mm spacing. The concrete used for this study is of grade M30. The yield strength of steel is calculated from experimental analysis and is taken as 387000kN/m2. Then the two slabs are taken for circular & square opening having size 75mm at an eccentric distance of 0.075mm. Then the slabs with opening are provided the FRP laminates around opening to and analysis is re-performed. Two types of FRP laminates are taken-CFRP & GFRP. The results obtained from this numerical study predicting ultimate load carrying capacity for all the slabs, crack pattern & load deflection curve are further compared with experimental results. The numerical analysis was performed by Finite Element software, ANSYS. SOLID65 element is used to model the concrete. LINK8 is used to model the steel reinforcement. SOLID165 is used to model the CFRP and GFRP wraps. The square slab is modelled using block volume of dimension (0.450*0.450*0.04) m. The thickness of the slab is taken along y-axis. The reinforcement is modelled by joining the keypoints. The slab is simply supported on all sides and the applied load is uniform. The direction of the applied load is in negative Y-direction and the direction of boundary condition is positive Y-direction. The results obtained from ANSYS are in good agreement with the experimental results. It is observed that the deflection of slabs with CFRP strengthening and circular opening was 25.6% less and square opening was 24% less.

2.3 Critical Discussion

Reviewing the literatures published in the last few decades it reveals that lots of researches have been carried out throughout the world in the field of strengthening of reinforced concrete slab with FRP laminates. The previous researchers have emphasized to get the extent of strengthening of the slab by considering different values of influencing parameters. It has been found by them the extent of strengthening is influenced by the type of FRP materials, their locations in the slab, the thickness and orientation of FRP layers, anchoring techniques, failure modes of FRP laminates, the reinforcement percentage in RC slab and the thickness of RC slab, the support conditions of RC slabs etc. They have tried to get the ultimate load in the form of concentrated load, distributed load, moment and cyclic load. But for practical implementation of this strengthening technique in the real life situation, the structural engineer must have a ready-made idea regarding the extent of enhancement of ultimate load, stiffness or the reduction of deflection of slab when a particular strengthening technique is used considering a specific set of parameters. This kind of concluding guideline, which is ready to use in the practical field, has not been found in the previous research. Hence there is still a need to search for a direct relation between the enhancement of ultimate load and the strengthening parameters for EBFRP strengthened reinforced concrete slab that can be implemented directly in the practical field of retrofitting or strengthening of RC slabs.

2.4 Present scope of study

It has been aimed in the present research work to find the relation between the extents of enhancement of ultimate load, stiffness and reduction of deflection with different parameters involved in the strengthening of RC slab with externally bonded FRP laminates following finite element approach. To reach the goal the work has been divided into two phases. In the first phase a finite element model of RC simply supported slab is developed using the finite element package ANSYS and the monotonically increasing transvers load is applied. The load and displacement response have been validated with the previous published literature [14]. In the second phase, the RC slab has been strengthened by attaching EBFRP in four different ways and same monotonically increasing transvers load is applied till its failure. The load displacement response coming from these studies have been compared with the same of un-strengthened slab and enhancement of ultimate load, stiffness and reduction in ultimate displacement have been assessed. The cracking patterns of the strengthened and un-strengthened slab are compared. Finally a series of plots have been developed to show the relation between the extents of enhancement of ultimate load with the portion of area of slab covered by FRP in different pattern of arrangements. Some equations are also tried to develop that will directly give the expected enhancement of ultimate load based on the portion of area of slab covered by FRP in different pattern of arrangements of FRP.

CHAPTER 3. METHODOLOGY (FE MODELLING OF RC SLAB)

3.1. Introduction

In the past few decades, FEM has become a major research focus for reinforced concrete structures. Choosing suitable elements, formulating proper material models and selecting proper solution method are required for a successful numerical simulation. The present work is aimed to analyze numerically the reinforced concrete slab strengthened with FRP laminates using FE method. This involves the proper choice of element, material properties, boundary conditions, solution techniques etc. In this chapter, different steps of FE modelling of the above-mentioned slab is described with reference to the features available in the FE software ANSYS and models prepared are analyzed to obtain load deformation response analytically. To perform a parametric study, the numerical analysis of a RC slab with or without FRP laminates is done using different types of support condition, FRP position, FRP thickness and FRP orientation. The structural analysis software suite, ANSYS, enables us to solve complex structural engineering problems and make better, faster design decisions. With finite element analysis (FEA) tools, it can customize and automate the simulations, and parameterize them to analyze multiple design scenarios. ANSYS Structural Mechanics software easily connects to other physics analysis tools, providing even greater realism in predicting the behavior and performance of complex products. In nutshell, this chapter discusses the steps followed and input data required to create the model of RC slab with or without FRP in ANSYS. The validation of the FE model thus prepared is done by comparing the load deformation response with the same obtained by the layered element approach followed by previous researchers. For this purpose, the geometry, reinforcement details, support condition, loading, etc. of the RC slab and the pattern of load deformation curve without FRP are taken from the numerical work done by S. Roychowdhury and reported in his Ph.D. thesis [8]. Here ANSYS 15 has been used to create the finite element model of RC slab with and without FRP. All the necessary steps taken to create the finite model are explained in detail.

3.2. Basic Finite Element Formulation

The numerical implementation of the finite element procedure used in the ANSYS software is based on the principles of virtual work or the postulation of minimum potential energy for assembly of the elements as formulated the following equilibrium equation:

$$[K]\{d\} + \{F\}P + \{F\}S + \{F\}g + \{F\}\varepsilon 0 - \{R\}=0$$

The stiffness matrix [K],

$$[K] = -\Sigma \int [B]^T [D][B]dv$$

The nodal force due to the surface load,

$$\{F\}P = -\Sigma \int [N]^T \{P\}dv$$

The nodal force due to the body load,

$$\{F\}g = - \Sigma \int [N]^T \{g\}dv$$

The nodal force due to the initial strain,

$$\{F\} \varepsilon 0 = \Sigma \int [N]^T [D]\{\varepsilon 0\}dv$$

where [N] is the shape function matrix; {d} is the vector of nodal displacement; {R} is the vector of applied nodal force; {p} is the vector of surface load; and {g} is the vector of body load. The ANSYS software uses mainly the Newton-Raphson (N-R) method to obtain the convergent solution of the nonlinear equilibrium equation which is actually iterative to update the stiffness matrix of the system.

3.3. Model of RC Slab Structure

The RC Slab is being modeled without FRP laminates and validation is performed with the previous experimental study by Taylor et.al. as reported by Owen *et.al* [14] and the

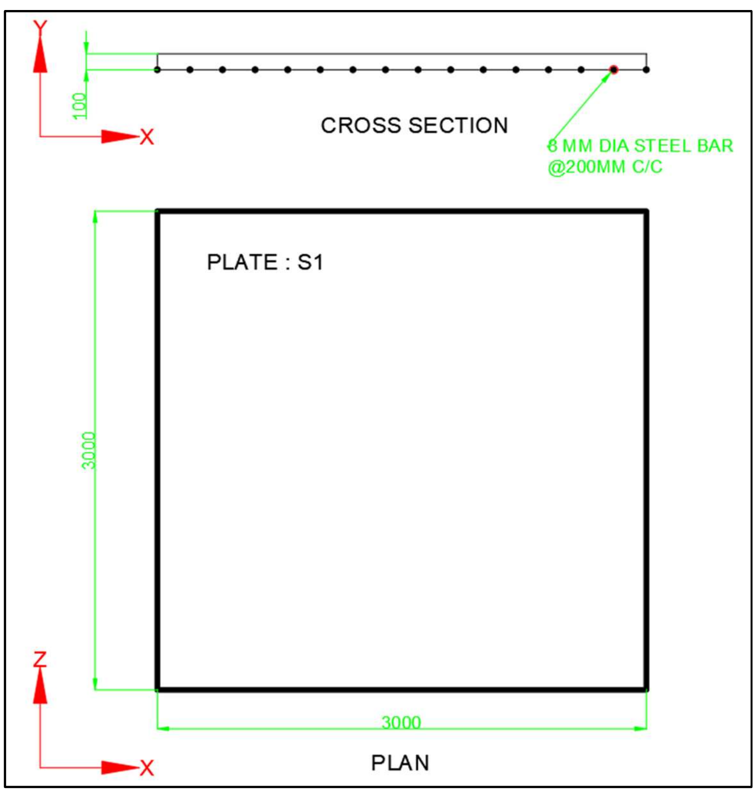


Fig. 2. Plan and Cross section of RC Slab

numerical analysis conducted by Owen *et.al* [14].

After validation of result extraction process, in this study there are five FE models of the slab out of which one control slab (S1) is without FRP laminates and four retrofitted slab (S2, S3, S4, S5) with FRP laminates, were modelled and analysis further proceeded to compare their results. The dimensions of all the slab specimens are identical. The plan dimensions of all the RC slab is 3000 mm (in x-direction) and 3000 mm (in z-direction). Thickness of slab is 100 mm (in y-direction). The slab is reinforced with two layers of reinforcing bars (FE 415) of 8 mm Tor@200mm c/c bothway provided at the bottom face only.

3.3.1. Elements used in ANSYS to Model Un-retrofitted and Retrofitted RC Slab

Element Types

While modeling the RC slab in ANSYS, different elements are used to model concrete, steel reinforcement and FRP laminates. SOLID65 element is chosen to model three dimensional concrete elements, LINK180 is adopted for flexural reinforcement bars. SOLID185 element has been taken to model the layer of FRP. Following are the brief descriptions of these elements along with the real constants required to be provided in ANSYS.

Table 1. Element Types used in present F.E. model

Material Type	ANSYS Element
Concrete	Solid 65
Steel Reinforcement	Link 180
FRP Sheets	Solid 185

SOLID65

SOLID65 is used in the present work for the 3-D modeling of concrete with and without reinforcing bars (rebar). The element is capable of cracking (in three orthogonal

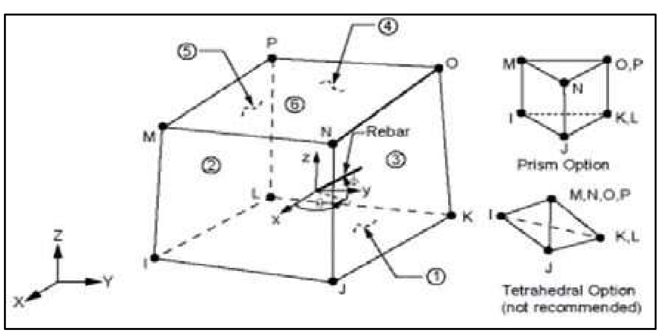


Fig. 3. SOLID65 element

directions) in tension and crushing in compression, plastic deformation, and creep. The most important aspect of this element is the treatment of nonlinear material properties. The rebar are capable of tension and compression, but not shear.

They are also capable of plastic deformation and creep. The element is defined by eight nodes having three degrees of freedom at each node: translations in the nodal x, y, and z directions. The concrete element SOLID65 is similar to a 3-D structural solid but become more superior with the addition of special cracking and crushing capabilities. Figure 3 shows SOLID65 element.

LINK180

LINK180 is a 3-D spar that is useful in a variety of engineering applications. The element can be used to model trusses, sagging cables, links, springs, and so on. The element is a uniaxial tension-compression element with three degrees of freedom at each node: translations in the nodal x, y, and z directions. Tension-only (cable) and compression-only (gap) options are supported. As in a pin-jointed structure, no bending of the element is considered. Plasticity, creep, rotation, large deflection, and large strain capabilities are included.

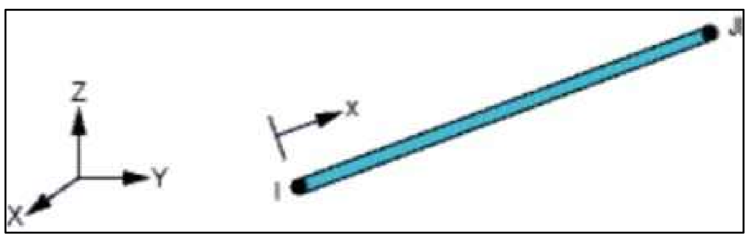


Fig. 4. LINK180 Geometry

LINK180 includes stress-stiffness terms in any analysis that includes large-deflection effects. Elasticity, isotropic hardening plasticity, kinematic hardening plasticity, Hill anisotropic plasticity, nonlinear hardening plasticity, and creep are supported. To simulate the tension-compression-only options, a nonlinear iterative solution approach is necessary.

SOLID185

SOLID185 is used for 3-D modeling of solid structures. It is defined by eight nodes having three degrees of freedom at each node: translations in the nodal x, y, and z directions. The element has plasticity, stress stiffening, creep, large deflection, and large strain capabilities. SOLID185 is available in two forms.

- Homogeneous Structural Solid
- Layered Structural Solid

In the current study layered structural Solid185 is used to simulate the various layer properties of GFRP laminates. The layered section definition is given by section

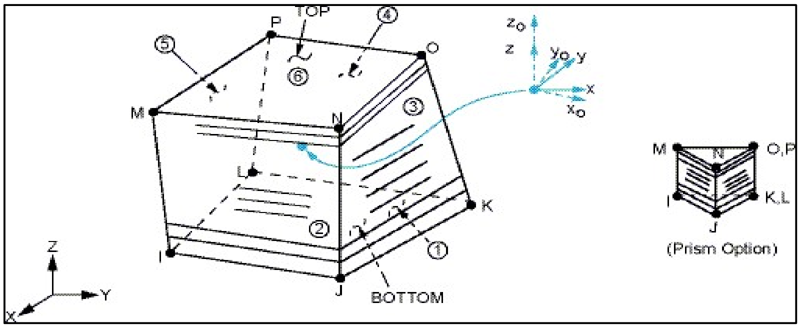


Fig. 5. SOLID185 Layered Structural Solid Geometry

(SEC*xxx*) commands in ANSYS.

3.3.2. Real Constants

The real constants for this model are shown in Table 2 here for individual elements contain different real constants.

Table 2. Real Constants for present Model

Real Constant Set	Element Type	Constants			
			Real Constants for Rebar 1	Real Constants for Rebar 2	Real Constants for Rebar 3
1	Solid 65	Material Number	0	0	0
		Volume Ratio	0	0	0
		Orientation Angle	0	0	0
		Orientation Angle	0	0	0
2	Link 180	No real constant is required			
3	SOLID 185	No real constant is required			

Real Constant Set 1 is used for the Solid65 element. The values can be entered for Material Number, Volume Ratio, and Orientation Angles. The material number refers to the type of material for the reinforcement. The volume ratio refers to the ratio of steel to concrete in the element. The orientation angles refer to the orientation of the reinforcement in the smeared model . ANSYS 15.0 allows the user to enter one rebar material in the concrete. Each material corresponds to x, y, and z directions in the element.

The reinforcement has uniaxial stiffness and the directional orientation is defined by the user. In the present study the slab is modeled using discrete reinforcement. Therefore, a value of zero was entered for all real constants which turned the smeared reinforcement capability of the Solid65 element. Real Constant Sets 2 is defined for the Link180 element. Here only the value for cross-sectional area is entered. No real constant is required for Real constant set 2 used for Link180 element and Real constant set 3 used for SOLID 185 element.

3.3.3. Sections

Section for this model is defined for the reinforcement element LINK180 and FRP element SOLID 185. For LINK180, Section subcategory Link is selected and the details are as follows:

Table 3. Section details for steel bar

Section ID:	1
Section Name:	8 mm Bar
Link Area:	50.21 mm^2
Added Mass:	0
Tension Key:	Tension and Compression

For SOLID 185, Section subcategory Shell is selected and the details are as follows:

Table 4. Section details for FRP laminates

Lay-up	Section ID:	2
	Section Name:	FRP
	Layer:	1
	Thickness:	3mm
	Material ID:	3
	Orientation:	0 degree
	Integration points:	3
	Trans shear stiffness (E11, E22, E33):	0.8, 0, 0.8
	Added Mass:	0
	Membrane Hourglass factor:	1
	Bending Hourglass factor:	1
	Drill stiffness factor:	1
Plot Section	Plot Section with ID:	2
	Range of Layers:	1 to 1

3.3.4. Modelling of Materials Behavior

In Reinforced concrete structures the behavior of concrete and reinforcing steel are different. Steel can be considered a homogeneous material and its material properties are generally well defined. Concrete is a heterogeneous material made up of cement, fine and coarse aggregates. Its mechanical properties scatter more widely and cannot be defined easily. For the purpose of analysis and design, however, in the macroscopic sense concrete is often considered a homogeneous material. The typical stages in the

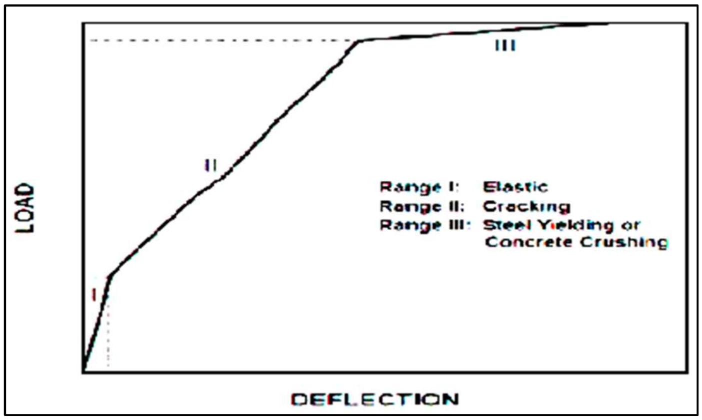


Fig. 6. Typical load-displacement response of RC element

load-deformation behavior of a reinforced concrete are illustrated as follows:

This nonlinear response can be divided into three ranges of behavior: the un-cracked elastic stage, the crack propagation and the plastic (yielding or crushing) stage. This nonlinear response is caused by three major effects:

- Tension crack of concrete
- Yielding of the reinforcement
- Crushing in compression of concrete

The stress-strain relation of concrete is not only nonlinear, but is different in tension than in compression. Because of these complexities' structures should be based on separate material models for reinforcing steel and concrete, which are then combined along with models of the interaction between the two constituents to describe the behavior of the composite reinforced concrete material.

Finite Element modelling of concrete

The concrete stress-strain relation, in compression, exhibits nearly linear elastic response up to about 30% of the compressive strength. This is followed by gradual softening up to the concrete compressive strength, when the material stiffness drops to zero. Beyond the compressive strength the concrete stress-strain relation exhibits strain softening until failure takes place by crushing.

- **<u>Concrete Models</u>**

  Many mathematical models are available in ANSYS to simulate the mechanical behavior of concrete. These can be divided into four main groups:

  - Orthotropic models,
  - Nonlinear elastic models,
  - Plastic models and
  - Endochronic models

The nonlinear response of concrete is simulated by linear elastic model with variable moduli. The model is particularly well suited for finite element calculations. When unloading takes place, the behavior can be approximated by moduli which are different from those under loading conditions. As a result, the variable moduli model is unable to describe accurately the behavior of concrete under high stress condition, near the compressive strength and in the strain softening range.

Failure Criteria for Concrete

The model is capable of predicting failure for concrete materials. Both cracking and crushing failure modes are accounted for. The two input strength parameters i.e., ultimate uniaxial tensile and compressive strengths are needed to define a failure surface for the concrete. Consequently, a failure criterion of the concrete due to a multiracial stress state can be calculated (William and Warnke 1975).

A three-dimensional failure surface for concrete is shown in Figure 7. The most significant nonzero principal stresses are in the x and y directions, represented by σxp, σyp , respectively. Three failure surfaces are shown as projections on the σxp - σyp plane. The mode of failure is a function of the sign of σzp (principal stress in the z direction). For example, if σxp and σyp are both negative (compressive) and σzp is slightly positive (tensile), cracking would be predicted in a direction perpendicular to σzp. However, if σzp is zero or slightly negative, the material is assumed to crush.

In a concrete element, cracking occurs under tension when the principal tensile stress in any direction lies outside the failure surface. After cracking, the elastic modulus of the concrete element is set to zero in the direction parallel to the principal tensile stress direction. Crushing occurs when all principal stresses are compressive and lie outside the failure surface; subsequently, the elastic modulus is set to zero in all directions, and the element effectively disappears.

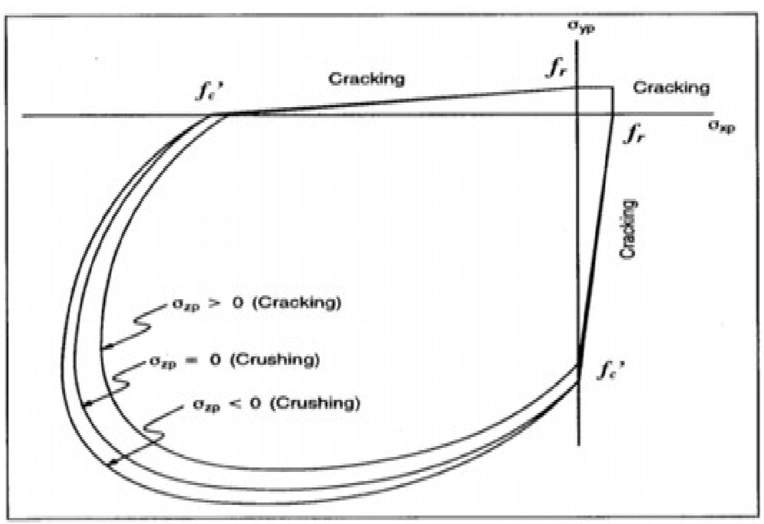


Fig. 7. Dimension failure surface for concrete

A pure “compression” failure of concrete is unlikely. In a compression test, the specimen is subjected to a uniaxial load. Secondary tensile strains induced by poisson's effect occur perpendicular to the load. Because concrete is relatively weak in tension, these actually cause cracking and the eventual failure. Therefore, in this study, the crushing capability was turned off and cracking of the concrete had controlled the failure of the finite element models. [2]

Finite Element Modeling Reinforcing Steel

Analysis of RC structures using the finite element method requires a simple accurate way of representing the reinforcement. Three alternative models have been usually used to simulate the behavior reinforcement, which are:

- Discrete reinforcement model.
- Embedded reinforcement model.
- Smeared reinforcement model.

<u>Discrete reinforcement model</u>

The reinforcement in the discrete model uses bar or beam elements that are connected to concrete mesh nodes. Therefore, the concrete and the reinforcement mesh share the same nodes and concrete occupies the same regions occupied by the reinforcement. A drawback to this model is that the concrete mesh is restricted by the location of the reinforcement and the volume of the steel reinforcement is not deducted from the concrete volume.

<u>Embedded reinforcement model</u>

The embedded model assumes that the reinforcing bar as an axial member is built into the iso-parametric element whose displacements are consistent with those of the element. Bars are restricted to lie parallel to the local coordinate axes of the basic element and perfect bond must be assumed between concrete and the reinforcement.

<u>Smeared reinforcement model</u>

The smeared model assumes that reinforcement is uniformly spread throughout the concrete elements in a defined region of the FE mesh. This approach is used for large-scale models where

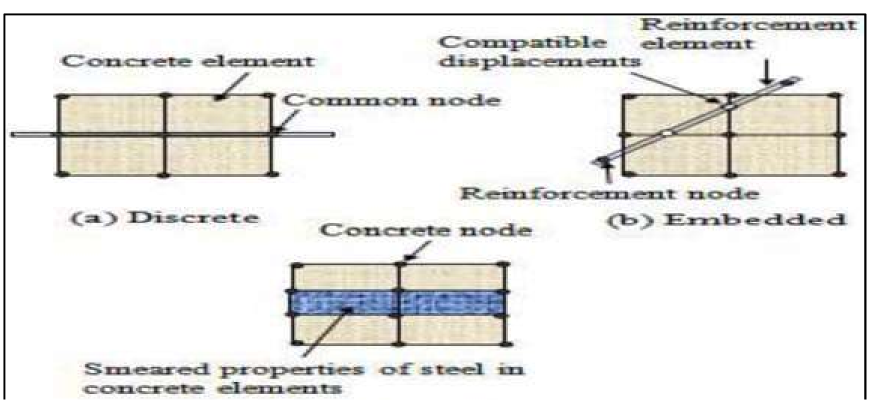


Fig. 8. Models for Reinforcement in Reinforced Concrete (a)Discrete; (b) embedded; and (c) smeared

Input for Material Properties

Material plays an important role in ANASYS modeling. Correct values of material properties have to be given as input in ANSYS. Cube compressive strength and all other properties of concrete are taken from the previous experimental study by Taylor et.al. and the numerical analysis has been conducted by Owen et.al. The modulus of elasticity of the concrete (Ec) and the Poisson's ratio (v) are mandatory information for the material definition. In ANSYS, EX is the modulus of elasticity of the concrete (Ec), and PRXY is the Poisson's ratio (v). The modulus is based on the equation (as per Cl. 6.2.3.1 of IS 456: 2000)

- f_{ck} = 35 Mpa
- $E_c = 5000\sqrt{fck}$= 29,580.39 MPa.
- Poison's ratio = 0.18

Parameters needed to define the material properties for the slab models are given in the following table.

Table 5. Material Properties for present Model

Material Model Number	Element Type	Material Properties		
		Multi Linear Isotropic		
		Reference point	**Strain**	**Stress (MPa)**
		1	0	0
		2	0.0002	06.65
		3	0.0004	12.6
		4	0.0006	17.85
		5	0.0008	22.4
1	SOLID 65	6	0.001	26.25
		7	0.0012	29.4
		8	0.0014	31.85
		9	0.0016	33.6
		10	0.0018	34.65
		11	0.002	35
		12	0.0035	35
		Non-metal Plasticity (Concrete)		
		Shear transfer coefficient for open crack		0.3
		Shear transfer coefficient for closed crack		1
		Uniaxial tensile cracking stress		3.79
		Uniaxial crushing stress		-1
		Biaxial crushing stress		0

1	SOLID 65	Biaxial crushing stress	0
		Ambient Hydrostatic stress state	0
		Biaxial crushing stress under ambient hydrostatic stress state	0
		Uniaxial crushing stress under ambient hydrostatic stress state	0
		Stiffness multiplier for cracked tensile condition	0
2	LINK 180	**Linear Isotropic**	
		E_x	2,00,000
		P_{RXY}	0.3
		Bilinear Isotropic	
		Yield stress	415
		Tang Modulus	-
3	SOLID185	**Linear Orthotropic**	
		E_x (MPa)	20700
		E_y (MPa)	7000
		E_z (MPa)	7000
		V_{xz}	0.26
		V_{xy}	0.26
		V_{yz}	0.3
		G_{xz}(MPa)	1520
		G_{xy}(MPa)	1520
		G_{yz}(MPa)	2650

Material no.1

Material model number 1 refers to the Solid 65 element. The Solid65 element requires linear isotropic and multi-linear isotropic material properties to model concrete properly. The multilinear isotropic material uses the Von-Mises failure criterion along

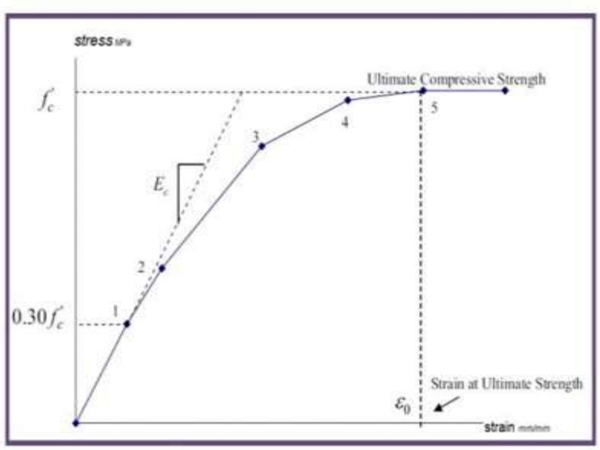


Fig. 9.Uniaxial Stress-strain curve for concrete

with the William and Warnke (1974) model to define the failure of the concrete. In ANSYS, Ex is the modulus of elasticity of the concrete (Ec), and PRXY is the poisson's ratio (v). The modulus is based on the equation (as per cl. 6.2.3.1 of IS 456: 2000).

In tension, the stress-strain curve for concrete is approximately linear elastic up to the maximum tensile strength. After this point, the concrete cracks and the strength decreases gradually to zero.

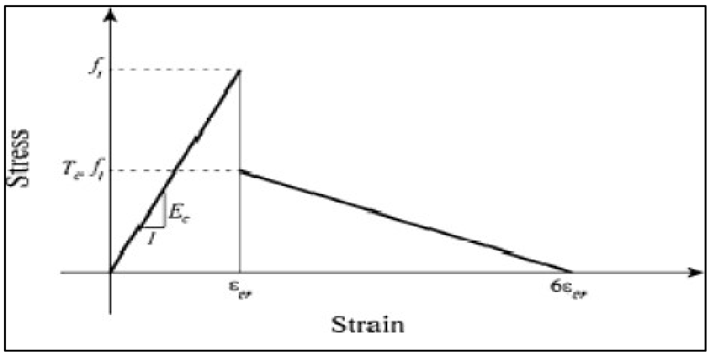


Fig. 10. Post cracking model of concrete in tension

The shear transfer coefficient for open and closed cracks represent the condition at the crack face while it is open (loaded) or closed (reversed load), respectively. The value of these coefficient ranges from 0.0 to 1.0, with 0.0 representing a smooth crack (complete loss of shear transfer) and 1.0 representing a rough crack (no loss of shear transfer) (ANSYS, Release 15.0 [27]). Convergence problem occurs when the shear transfer coefficient for the open crack drops below 0.2. No deviation of response occurs with the change of coefficient. The uniaxial cracking stress is based upon the modulus of rupture. This value is determined using the following equation (as per Cl.6.2.2 of IS 456; 2000[IS 456]):

$$f_{cr} = 0.7\sqrt{f_{ck}}$$

Material no.2

Material Model Number 2 refers to the Link 180 element. The Link 180 element is being used for steel reinforcement and it is assumed to be bilinear isotropic. The

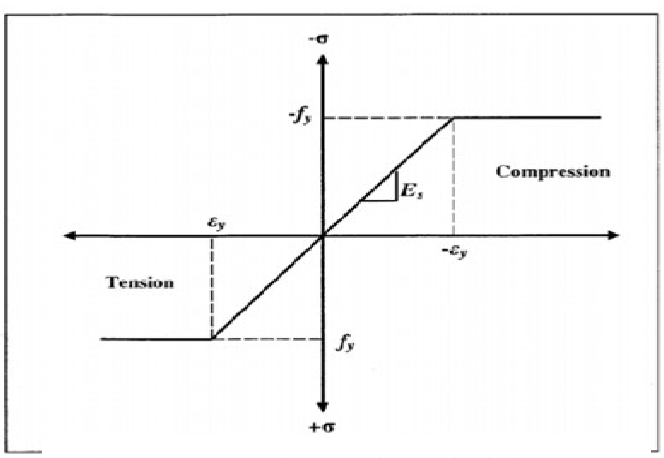


Fig. 11. Stress-strain curve for steel reinforcement

bilinear isotropic material is also based on the Von Mises failure criteria. The bilinear model requires the yield stress (fy), as well as the hardening modulus of the steel to be defined. The steel for the finite element models was assumed to be an elastic-perfectly plastic material and identical in tension and compression. Figure 3.10 shows the stress-strain relationship used in the study.

Material no.3

As for the modeling of GFRP composites in ANSYS software, a linear orthotropic material model is used. Material properties for GFRP as specified by previous literature are taken in the present study and shown in Table 5

3.3.5. Geometrical Modelling of Present Finite Element RC Slab Model

Entity Creation

The two-way RC slab is modeled as a volume. The thickness of the slab model is 100 mm, with length 3000 mm and width 3000 mm. The dimensions for the concrete volume are shown in Table 3.4. The volume is shown in the following figure, SOLID 65 element are chosen to discretize this concrete volume.

Table 6. Dimensions for concrete volume

ANSYS	Concrete (mm)	
X1, X2 X - coordinates	0	3000
Y1, Y2 Y- coordinates	0	100
Z1, Z2 Z - coordinates	0	3000

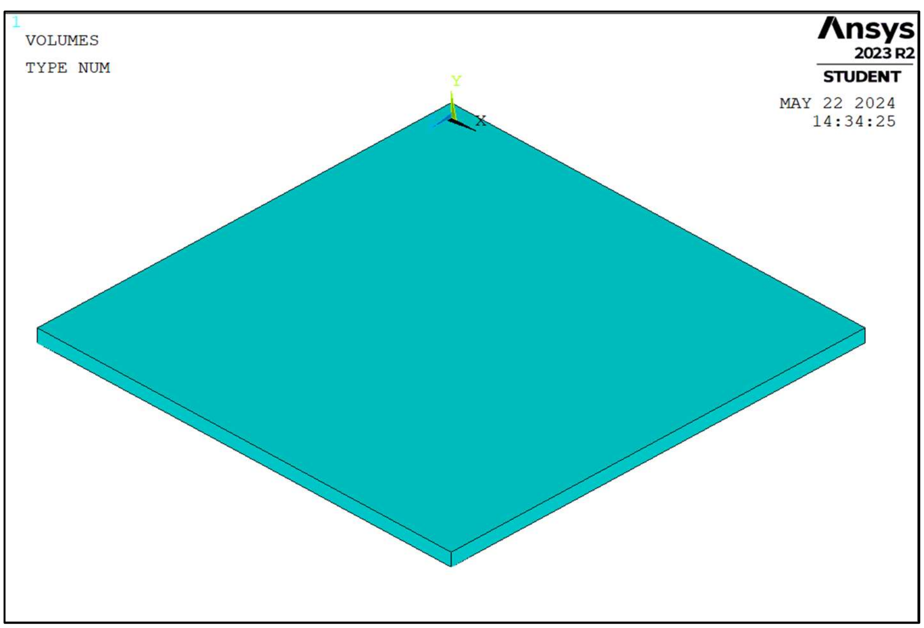


Fig. 12. Volume created in ANSYS

Link180 elements are used to create the flexural reinforcement as shown in figure 13. The reinforcement elements are connected to the nodes of SOLID 65 elements. Solid 185 elements are employed to model the GFRP composites that are attached at the bottom surface of the lowermost SOLID 65 elements like the LINK 180 elements. The

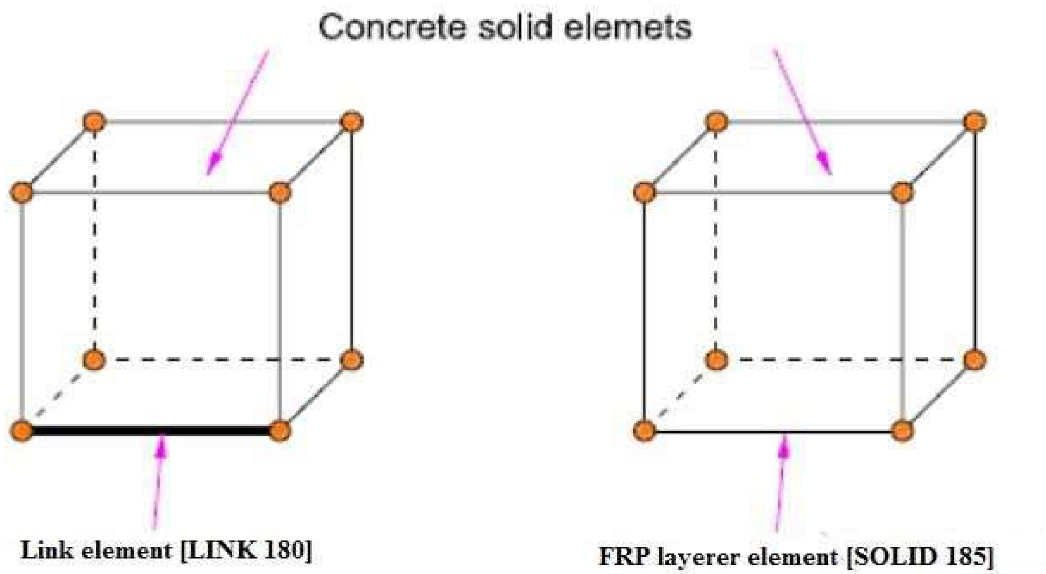


Fig. 13. Element connectivity: (a) Concrete solid element and link element (left);
(b) Concrete solid element and FRP layered elements (right)

volumes are created for individual FRP strip where we have intended to give the GFRP layers. The perfect bonding was assumed between elements. The same approach was adopted for FRP composites as shown in Fig.13. The perfect bond assumption may be achieved using the high strength of the epoxy or by mechanical anchors used to attach the FRP sheets to the control slab.

Meshing

For more exact results from the Solid65 element, the use of a rectangular mesh is recommended. For the purpose of present analysis, the concrete volume divided into 4 layers with two reinforcement steel layers throughout the thickness of the slab shown in fig.12. There are 900 numbers of elements at the top surface of the slab when meshed the slab.

Table 7. Mesh Attributes for the Model

Model Parts	Element Type Number	Material Number	Real Constant	Section Number
Concrete slab	SOLID 65	1	1	N/A
Reinforcement bar	LINK 180	2	N/A	1
GFRP layer	SOLID 185	3	N/A	2

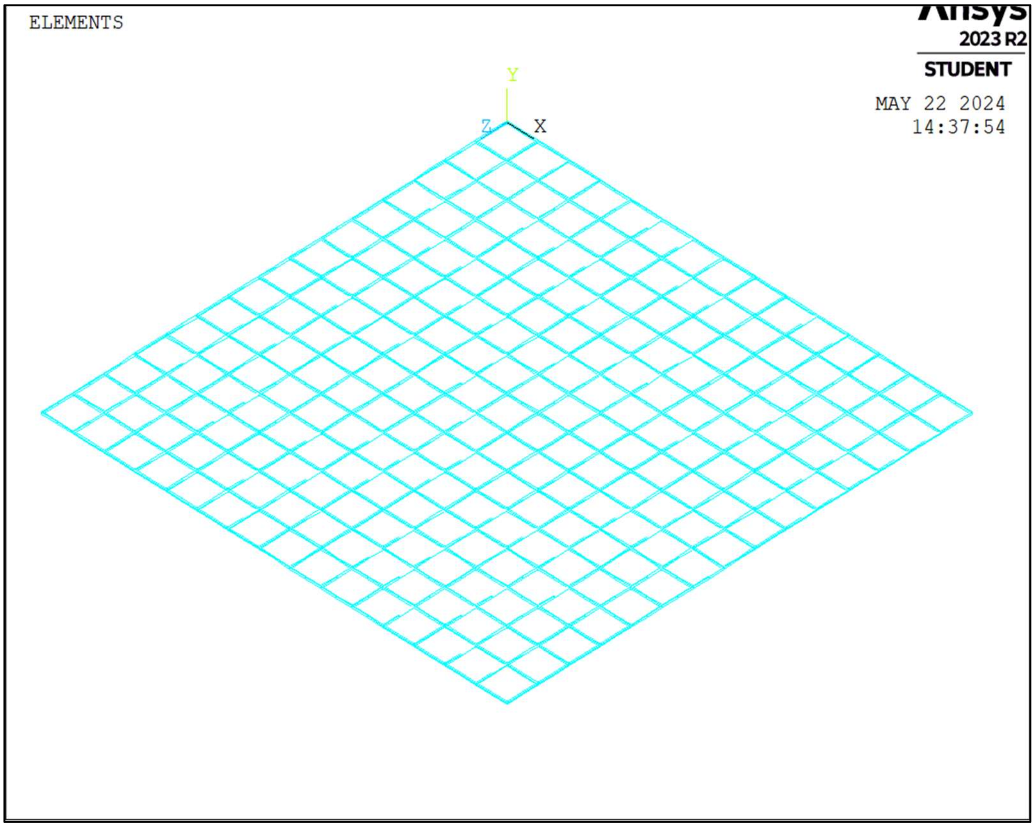


Fig. 14. RC Slab Rebar Arrangement

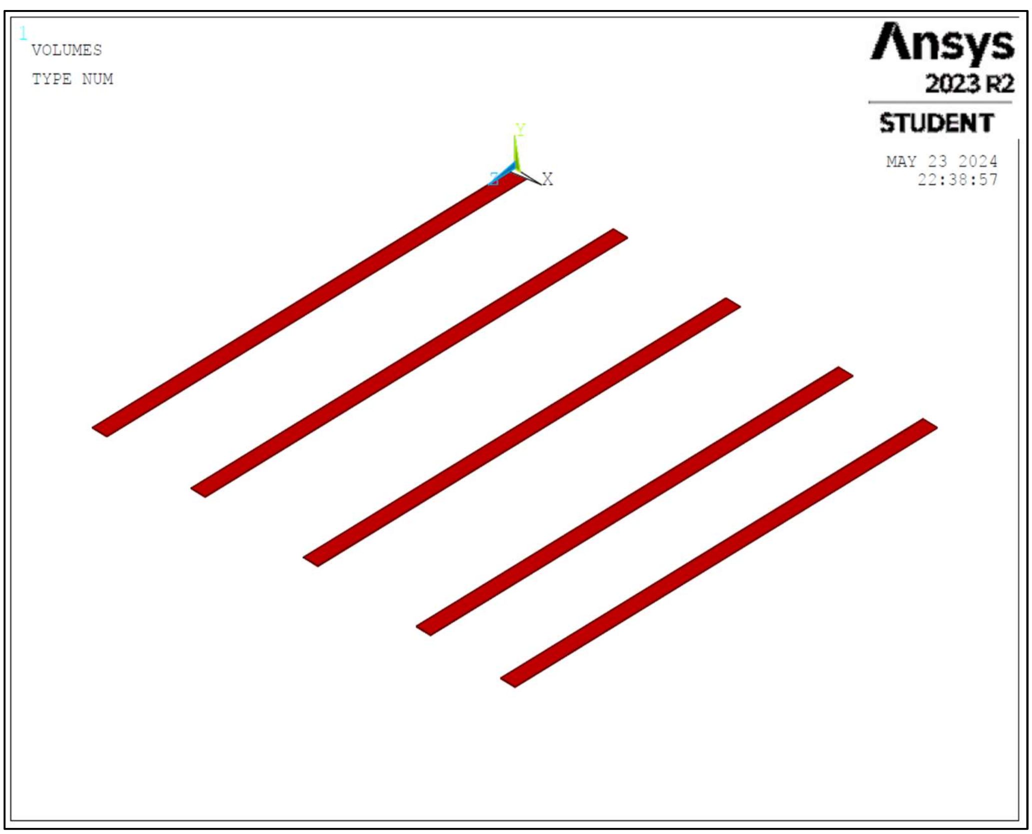


Fig. 15. One Sample FRP Arrangement

3.3.6. Loading & Boundary Condition

Displacement boundary conditions are needed to constrain the model to get a unique solution. To ensure that the model acts the same way as the experimental and analytical slab boundary conditions need to be applied. The support was modeled in such a way that a roller was created.

Two single lines of nodes along the X direction (at X=0, Y=0 and X=3000, Y=0) were given constraint in the UY, and UX directions, applied as constant values of 0. Similarly, two single lines of nodes along the Z direction (at Z=0, Y=0 and Z=3000, Y=0) were given constraint in the UY, and UZ directions, applied as constant values of 0. By doing this, the slab will be allowed to rotate at the support and also translational effect also considered.

A uniformly distributed load was applied over the span of the slab as increased gradually by 10 KN in each increment. This uniformly distributed load is applied as a point load on each and every top nodes of that slab. There were total 961 number of nodes at the top of the slab among these nodes 4 corner node, 116 edge (support edge) nodes and 841 interior nodes. The Corner nodes loaded as 1/4th times and the Edge nodes loaded as 1/2th times of the load at each interior node.

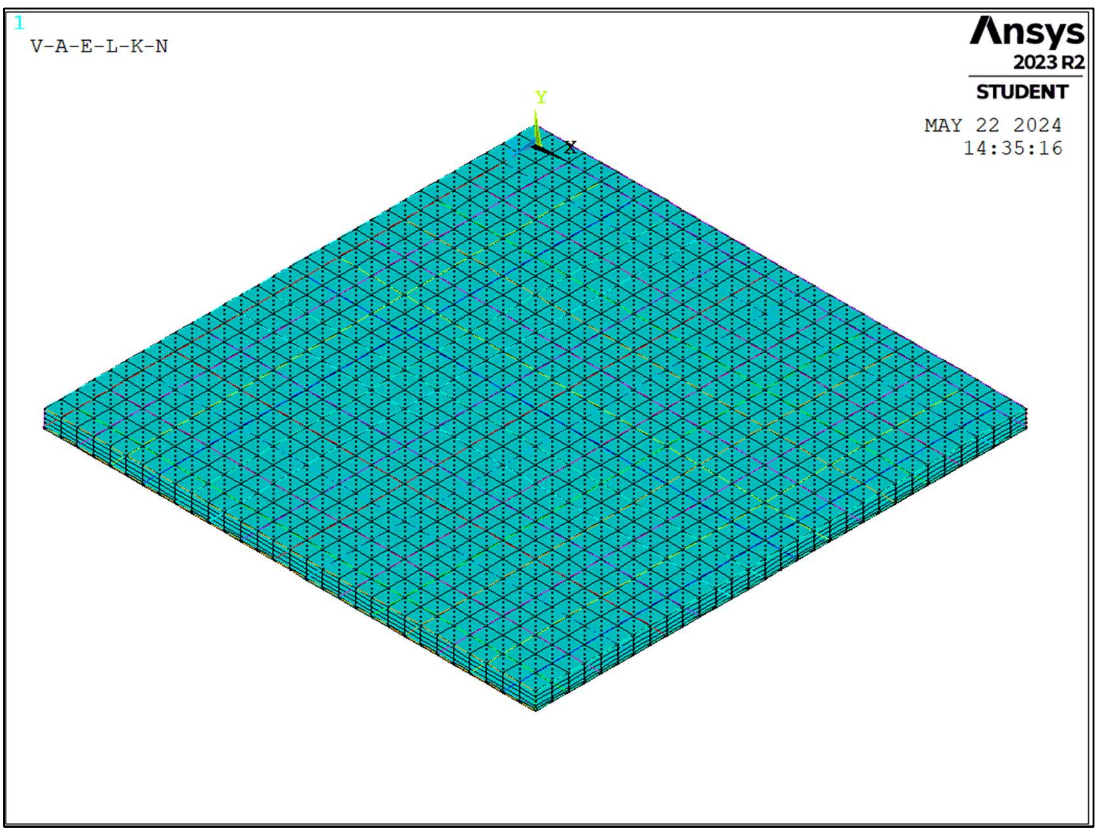


Fig. 16. RC slab complete ANSYS model with mesh, concrete volume, rebar arrangement, FRP, Boundary Conditions & Loadings

3.3.7. Solution Control for Non-Linear Solution

In nonlinear analysis, the total load applied to a finite element model is divided into a series of load increments called load steps. After the completion of each incremental solution, the stiffness matrix of the model is adjusted to reflect nonlinear changes in structural stiffness before proceeding to the next load increment. The Newton–Raphson equilibrium iterations for updating the model stiffness are used in the nonlinear solutions. Prior to each solution, the Newton-Raphson approach assesses the out-of-balance load vector, which is the difference between the restoring forces (the loads corresponding to the element stresses) and the applied loads. Subsequently, the program carries out a linear solution using the out-of-balance loads and checks for convergence. If convergence criteria are not satisfied, the out-of balance load vector is re-evaluated, the stiffness matrix is updated, and a new solution is carried out. This iterative procedure continues until the results converge. In this study, convergence criteria for the reinforced concrete solid elements are based on force and displacement, and the convergence tolerance limits are set as 0.1 for both force and displacement in order to obtain the convergence of the solutions [4].

For the nonlinear analysis, automatic time stepping in the ANSYS program predicts and controls the load step sizes. Based on the previous solution history and the physics of the models, if the convergence behavior is smooth, automatic time stepping will increase the load increment upto the given maximum load step size. If the convergence behavior is abrupt, automatic time stepping will bisect the load increment until it is equal to a selected minimum load step size.

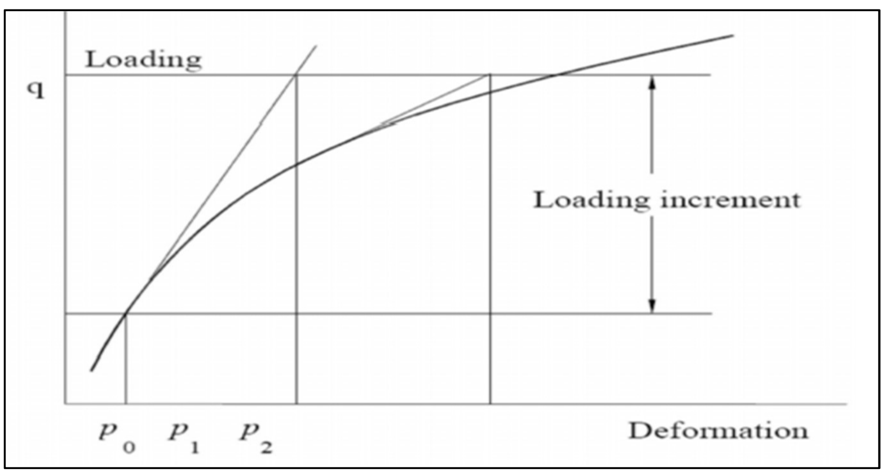


Fig. 17. Nonlinear solutions as Newton-Raphson approach

The maximum and minimum load step sizes are required for the automatic time stepping. The total load is to be divided into number of suitable load steps (load increments) by conducting a few trial analyses until a smooth load versus deflection curve is obtained.

In ANSYS, the Solution Controls command dictates the use of a linear or non- linear solution for the finite element model. Typical commands utilized in a nonlinear static analysis are shown in the following table.

Table 8. Commands used to Control Nonlinear Analysis

Analysis Options	**Small Displacement**
Calculate Prestress Effects	No
Time at End of Load step	1
Automatic Time Stepping	On
Time step size	0.01
Minimum Time step	0.001
Maximum Time step	0.1
Write items to Result File	All Solution Items
Frequency	Write Every Substep

In the particular case considered in this thesis the analysis is small displacement and static. The time at the end of the load step refers to the ending load per load step. Table 3.6 shows the first load step taken in the analysis. The sub steps are set to indicate load increments used for this analysis. The commands used to control the solver and outputs are shown as follows.

Table 9. Commands Used to Control Output

Equation Solvers	**Sparse Direct**
Number of Restart Files	1
Frequency	Write Every Sub-

The commands used for the nonlinear algorithm and convergence criteria are shown in the following table. All values for the nonlinear algorithm are set to defaults. The values for the convergence criteria are set to defaults except for the tolerances. The following table shows the commands used for the advanced nonlinear settings. The program behavior upon non-convergence for this analysis is set such that the program will terminate but not exit. The rest of the commands are set to defaults as in ANSYS help.

Table 10. Nonlinear Algorithm and Convergence Criteria Parameters

Line search		Off
DOF solution predictor		Prog chosen
Maximum number of iteration		350
Cutback control		Cutback according to predicted number of iteration
Equiv. plastic strain		0.15
Explicit creep ratio		0.1
Implicit creep ratio		0
Incremental displacement		10000000
Points per cycle		13
Set convergence criteria		
Label	F	U
Ref. value	Calculated	Calculated
Tolerance	0.1	0.1
Norm	L2	L2
Min. Ref.	Not applicable	Not applicable

Table 11. Advanced Nonlinear Control Settings Used

Program behavior upon non-convergence	Terminate but do not exit
Nodal DOF solution	0
Cumulative iteration	0
Elapsed time	0
CPU time	0
Stabilization	Constant Stabilization
Control	Energy dissipation
Value	0.5

3.4. Steps for the development of the slab model with or without FRP

ANSYS program system consists of a solution core and several user interfaces. The solution core offers capabilities for variety of structural analysis tasks, such as: stress and failure analysis, transport of heat and humidity, time dependent problems (creep, dynamics), and their interactions. Solution core offers a wide range of 2D and 3D continuum models, libraries of finite elements, material models and solution methods. User interfaces are specialized on certain functions and thus one user interface need not necessarily provide access to all features of ANSYS solution core. This limitation is made in order to maintain transparent and user friendly applications of ANSYS.
The ANSYS program has three main processing windows

1. **Pre-processor**:	In pre-processor window, following steps are performed: - **Step1:** Different elements, compatible with different materials are chosen as described in section 3.4 **Step2**: Real constants are given for solid 65 as described in section 3.4.2 **Step3:** Various material models are created depending on different material properties as described in section 3.5.3 **Step**: Section details are given for 1 link section and 1 shell section which latte used for element type Link180 and Solid185. **Step4:** Solid geometry for concrete body of FE model is generated by creating different size of block as a volume. **Step5:** Solid volumes are then discretized into a finite number of nodes and element followed by assigning element type, real constant, material property to the element and meshed volume is created. **Step6:** Node merging followed by key point merging is done to add different meshed volume and create a single entity object. Following the above steps PCC structure is modeled. **Step7:** As the discrete model of reinforcement is used in the current study the reinforcement is modeled by creating element through nodes followed by assigning appropriate material properties. Following this step RCC structure i.e. control slab is modeled. **Step8:** By following the above stated steps of volume creation and meshing different retrofitted specimen was also created under different retrofitting scheme/pattern which are presented in the next section.

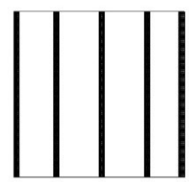
2. **Solution**:	In solution window following step is performed: - **Step9:** Boundary condition and loading is applied and run the program for analyzing those specimens. A loaded specimen model with boundary condition.
3. **General Post-processor**:	In Post-processor window following step is performed: - **Step10:** A wide range of graphical and numerical results i.e. output of analysis is generated and presented in Result and Discussion chapter.

3.5. Different Retrofitted Setup of RC slab Models for present study

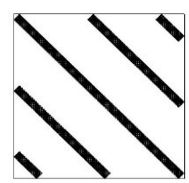
The present study encompasses the suitability of different retrofitting mode for RC two-way slab strengthened with FRP. For this purpose, different retrofitting setup have been adopted and followed in the modeling of retrofitted RC two-way slab in ANSYS.

- **Setup 1** (By Varying the FRP Location at the Bottom of the RC Slab)

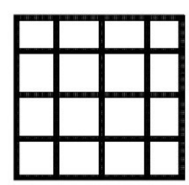
1. SS2: Full length FRP strips placed along a single direction parallel to the edge at an equal interval.



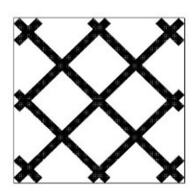
2. SS3: Full length FRP strips placed along a single diagonal direction at an equal interval.



3. SS4: Full length FRP strips placed along mutually perpendicular direction parallel to the edge at an equal interval.



4. SS5: Full length FRP strips placed along mutually perpendicular diagonal direction at an equal interval.



- **Setup 2** (By Increasing the width of FRP strip or FRP covered area of Slab bottom surface at different locations of the RC Slab).

  By increasing the FRP area from covered area of Slab bottom surface 15% to 100% gradually for all Four FRP locations of the slab.

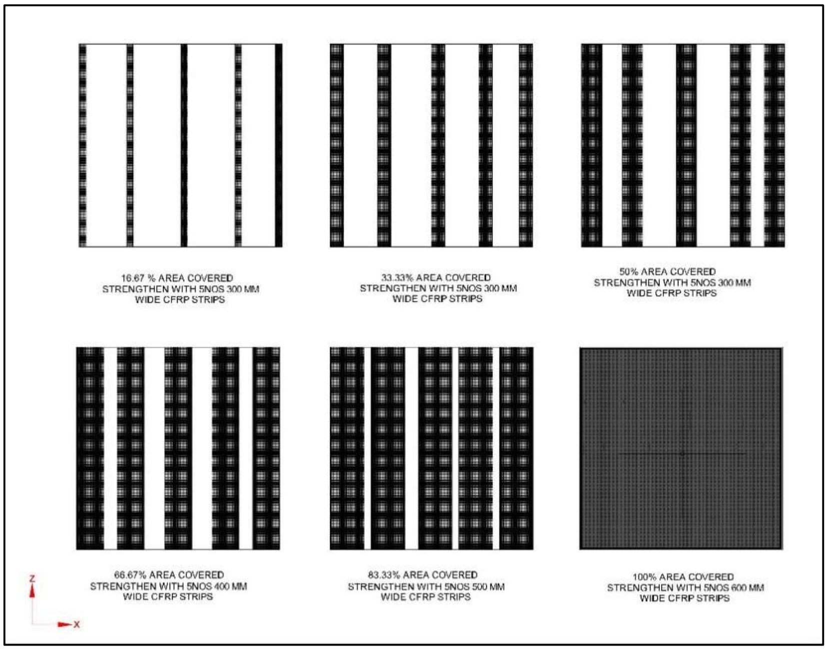


Fig. 18. Increasing the FRP area along support edge

Labeling of different slabs with variation of FRP width under SS2:

1. SS21: 5 Nos 100 mm width full length FRP strips placed along a single direction parallel to the edge at a suitable interval, FRP strip Cover the surface of slab 16.67%
2. SS22: 5 Nos 200 mm width full length FRP strips placed along a single direction parallel to the edge at a suitable interval, FRP strip Cover the surface of slab 33.33%
3. SS23: 5 Nos 300 mm width full length FRP strips placed along a single direction parallel to the edge at a suitable interval, FRP strip Cover the surface of slab 50%
4. SS24: 5 Nos 400 mm width full length FRP strips placed along a single direction parallel to the edge at a suitable interval, FRP strip Cover the surface of slab 66.67%
5. SS25: 5 Nos 500 mm width full length FRP strips placed along a single direction parallel to the edge at a suitable interval, FRP strip Cover the surface of slab 83.33%
6. SS26: 5 Nos 600 mm width full length FRP strips placed along a single direction parallel to the edge at a suitable interval, FRP strip Cover the surface of slab 100%

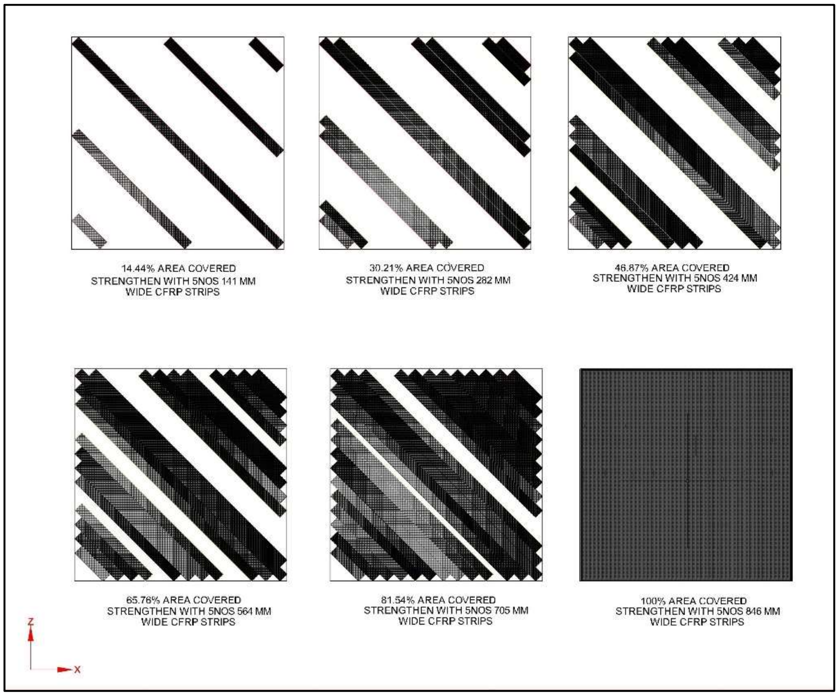


Fig. 19. Increasing the FRP area along continuous edge

Labeling of different slabs with variation of FRP width under SS3:

1. SS31: 5 Nos 141 mm width full length FRP strips placed along a single diagonal direction at a suitable interval, FRP strip Cover the surface of slab 14,44%
2. SS32: 5 Nos 282 mm width full length FRP strips placed along a single diagonal direction at a suitable interval, FRP strip Cover the surface of slab 30.21%
3. SS33: 5 Nos 424 mm width full length FRP strips placed along a single diagonal direction at a suitable interval, FRP strip Cover the surface of slab 46.87%
4. SS34: 5 Nos 564 mm width full length FRP strips placed along a single diagonal direction at a suitable interval, FRP strip Cover the surface of slab 65.76%
5. SS35: 5 Nos 705 mm width full length FRP strips placed along a single diagonal direction at a suitable interval, FRP strip Cover the surface of slab 81.54%
6. SS36: 5 Nos 846 mm width full length FRP strips placed along a single diagonal direction at a suitable interval, FRP strip Cover the surface of slab 100%

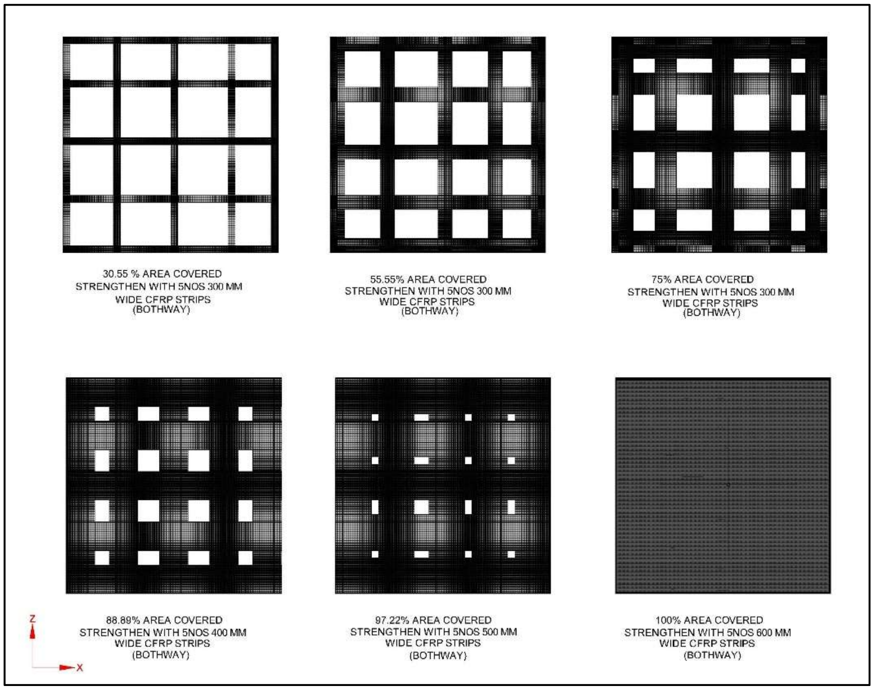


Fig. 20. Increasing the FRP area along diagonal

Labeling of different slabs with variation of FRP width under SS4:

1) SS41: 5 Nos 100 mm width full length FRP strips placed along mutually perpendicular direction parallel to the edge at a suitable interval, FRP strip Cover the surface of slab 30.55%
2) SS42: 5 Nos 200 mm width full length FRP strips placed along mutually perpendicular

   direction parallel to the edge at a suitable interval, FRP strip Cover the surface of slab 55.55%
3) SS43: 5 Nos 300 mm width full length FRP strips placed along mutually perpendicular direction parallel to the edge at a suitable interval, FRP strip Cover the surface of slab 75%
4) SS44: 5 Nos 400 mm width full length FRP strips placed along mutually perpendicular direction parallel to the edge at a suitable interval, FRP strip Cover the surface of slab 88.89%
5) SS45: 5 Nos 500 mm width full length FRP strips placed along mutually perpendicular direction parallel to the edge at a suitable interval, FRP strip Cover the surface of slab 97.22%
6) SS46: 5 Nos 600 mm width full length FRP strips placed along mutually perpendicular direction parallel to the edge at a suitable interval, FRP strip Cover the surface of slab 100% (2 layers).

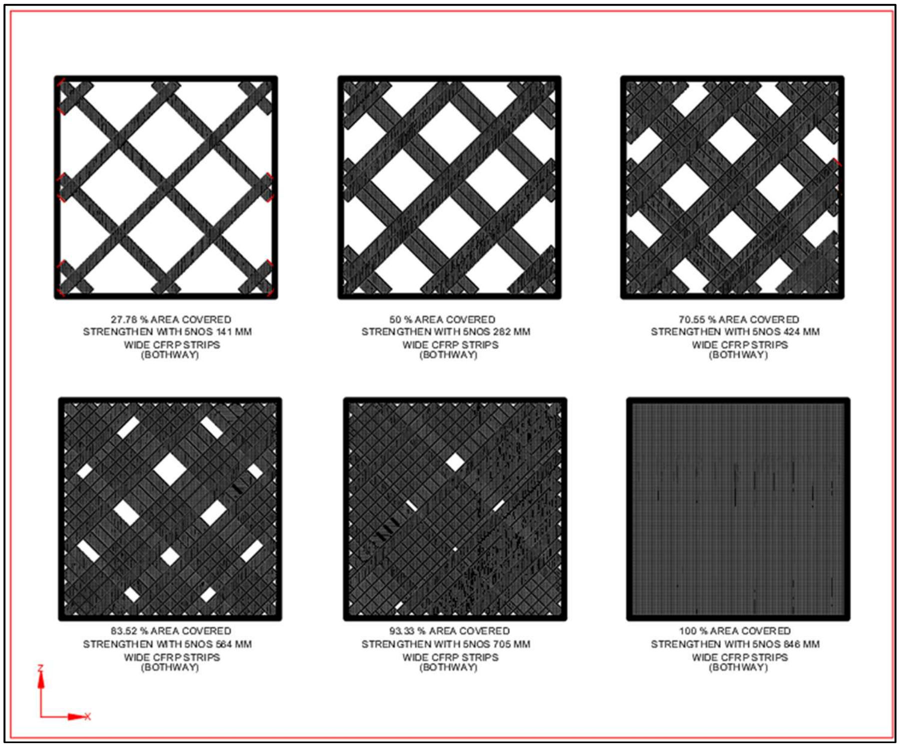


Fig. 21. Increasing the FRP area along diagonal

Labeling of different slabs with variation of FRP width under SS5:

1) SS51: 5 Nos 141 mm width full length FRP strips placed along mutually perpendicular diagonal direction at a suitable interval, FRP strip Cover the surface of slab 27.78%
2) SS52: 5 Nos 282 mm width full length FRP strips placed along mutually perpendicular

   diagonal direction at a suitable interval, FRP strip Cover the surface of slab 50%
3) SS53: 5 Nos 424 mm width full length FRP strips placed along mutually perpendicular diagonal direction at a suitable interval, FRP strip Cover the surface of slab 70.55%
4) SS54: 5 Nos 564 mm width full length FRP strips placed along mutually perpendicular diagonal direction at a suitable interval, FRP strip Cover the surface of slab 83.52%
5) SS55: 5 Nos 705 mm width full length FRP strips placed along mutually perpendicular diagonal direction at a suitable interval, FRP strip Cover the surface of slab 93.33%
6) SS56: 5 Nos 846 mm width full length FRP strips placed along mutually perpendicular diagonal direction at a suitable interval, FRP strip Cover the surface of slab 100% (2 layers).

CHAPTER 4. VALIDATION OF RESULT DERIVED FROM ANSYS, UTILIZING FINITE ELEMENT MODEL OF RC SLAB

4.1. Validation of proposed model

For the purpose of validation of the present numerical approach, for the retrofitted and un-retrofitted RC slab a result comparison was performed and analyzed. A simply supported reinforced concrete slab analyzed numerically earlier by Owen et.al. has been taken presently for finite element analysis using ANSYS. This simply supported square reinforced concrete slab was tested under uniformly distributed mechanical load is analyzed here for the verification of the results obtained from the present formulation with ANSYS.

The details of this slab thus taken from the same reference are used to prepare the model in ANSYS. The plan dimension of the full slab is 1980 mm (in x-direction) and 1980 cm (in z-direction). Thickness of slab is 51 mm. The uniformly spaced reinforcing bars are provided at the bottom face of the slab only. All nodes at simply supported boundary are assumed to be free in the horizontal direction. The details of the problem i.e. geometrical data, finite element discretization, boundary condition and material properties of concrete and steel shown in Figure 23. Material properties for concrete and steel are considered from the same reference and given here in Table 12. For the purpose of present analysis, 8-noded SOLID 65 elements are used. Seven concrete layers across the thickness, as considered previously, are replaced by seven SOLID 65 elements. The steel reinforcements are modeled using LINK 180 elements connecting the nodes of SOLID 65 elements. The LINK 180 elements in both the steel layers has unidirectional properties parallel to each of the two the longitudinal directional of the elements. The finite element discretization of the present model is shown in Figure 22. Uniformly distributed load is increased gradually by 0.56 KN in each increment.

Table 12. Material Properties for Concrete and Steel

Concrete		Steel	
Young's Modulus	32420 N/mm^2	Young's Modulus	206910 N/mm^2
Poison's Ratio	0.18	Yield Stress	375.9 N/mm^2
Ultimate Comp. Strength	35 N/mm^2	Thermal Coeff.	0.00001
Ultimate Tensile Strength	3.79N/mm^2		
Tension Stiff. Coeff.α	0.6		
Tension Stiff. Coeff.ε_m	0.002		
Thermal Coeff.	0.00001		
Ultimate Comp. Strain ε	0.0035		

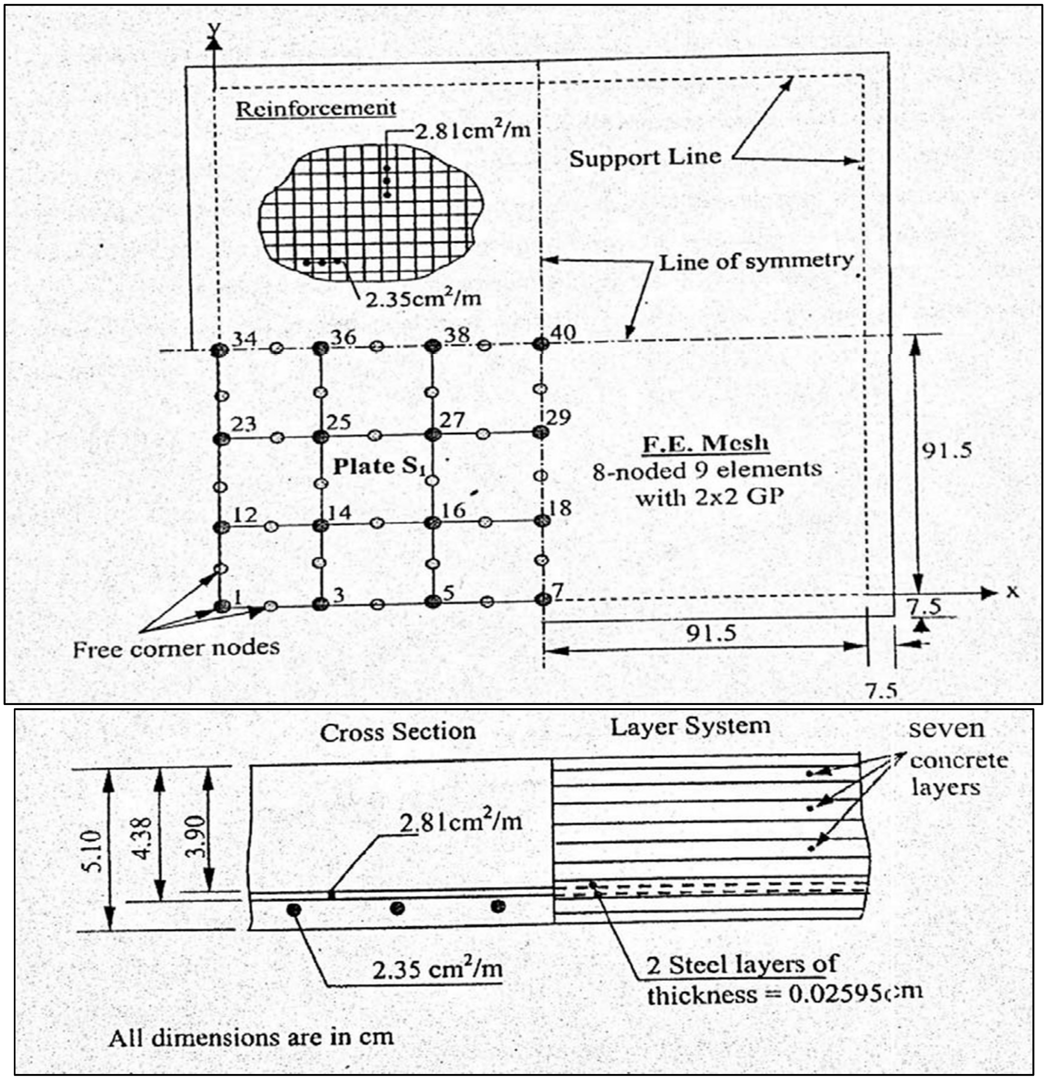


Fig. 23. Details of RC slab and its finite element representation

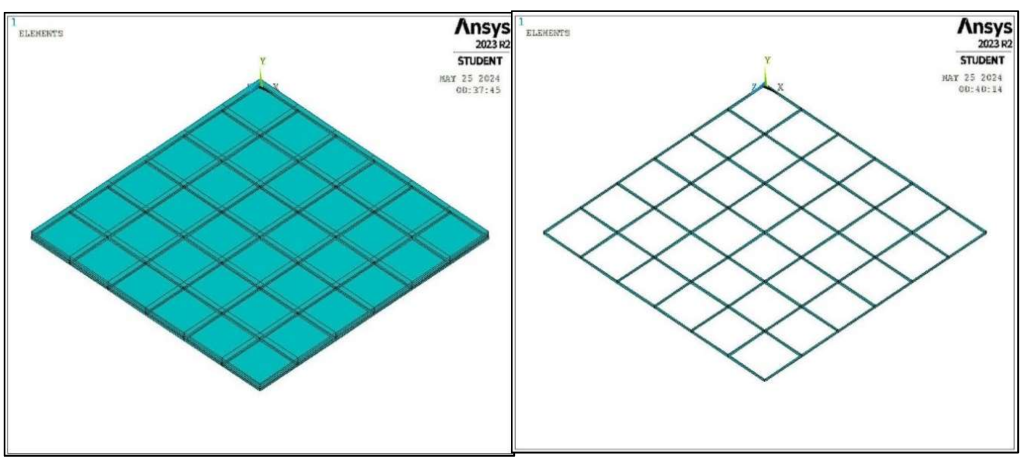


Fig. 22. a) ANSYS model of RC slab in X-Z plane with 6 x 6 mesh (left)
b) Modelling of reinforcement bars (right)

For the purpose of the validation, the numerical results i.e. the load deflection curve are compared with the load deflection response of this slab obtained by Taylor et.al. From his experimental study and the same obtained by Owen et.al. The finite element solutions coming from the present numerical model has been superimposed as shown in following figure to compare the present solution with the earlier solutions.

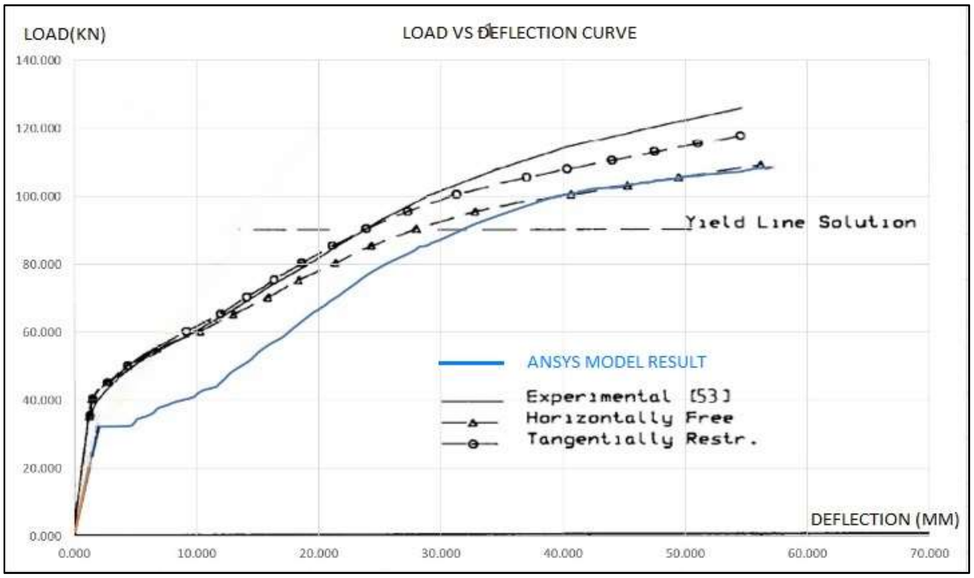


Fig. 24. Comparision of load deflection curve of the present ANSYS model with the same obtained by other previous researchers

It is clear from the comparison shown in Figure 24 that the present numerical solution is identical with the other three solutions in the elastic range. But, the behavior of the slab just after the development of initial cracks in the present model differs with the previous models. This may due to the fact that the post-cracking behavior of concrete considered in the present model is not matching with the model considered in the previous numerical analysis. But the load-deflection pattern is almost matching with the experimental one obtained by Taylor et.al. This indicates that the present approach for finite element analysis of reinforced concrete slab using ANSYS can be considered for further parametric study.

CHAPTER 5. RESULTS OF NUMERICAL EXPERIMENTS & DISCUSSIONS

5.1 Introduction

The finite element models of reinforced concrete slab strengthened with FRP laminates prepared using the software ANSYS as described in the previous chapter are analyzed against gradually increasing uniformly distributed transverse load to assess the suitability and effectiveness of the process of strengthening of slab using FRP. The results of this analysis of a large number of RC slab are presented and discussed in this chapter. As stated in the chapter-3 the present RC slabs FE models physical and material properties utilized and simulated in ANSYS to extract numerical experiment results. To assess the applicability of the present approach, different case studies have been performed by varying different parameters like location of FRP laminates, the width of FRP band etc. All these results are reported in the following sections.

5.2 Analysis of Control Slab or un-retrofitted slab (SS1)

First one controlled slab or un-retrofitted slab Finite element modelled with the dimensions, physical and material properties, loading and boundary condition stated in the chapter-3. Then numerical result extracted from ANSYS and plotted. This result latter helped us for the comparison study for different retrofitting configuration we have considered.

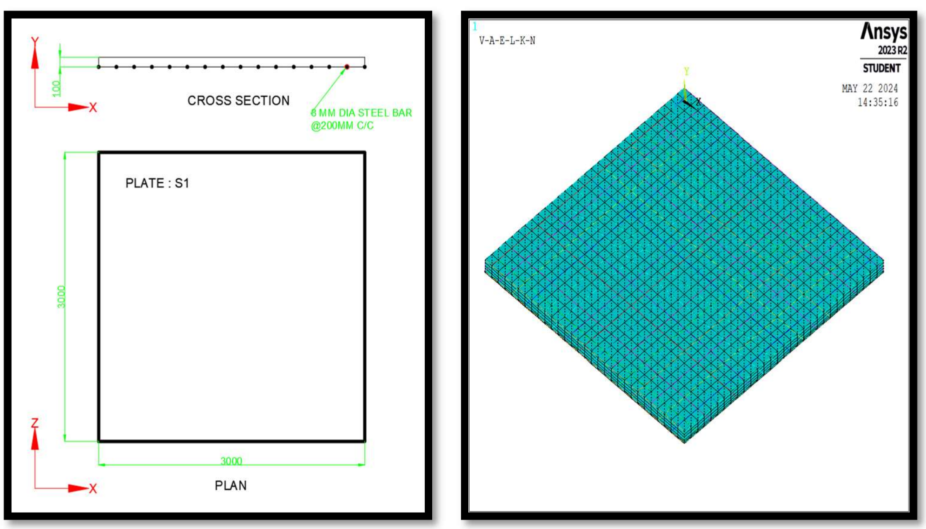


Fig. 25. a) Plan & section dimension of the slab (left) b) FEM Model in ANSYS (right)

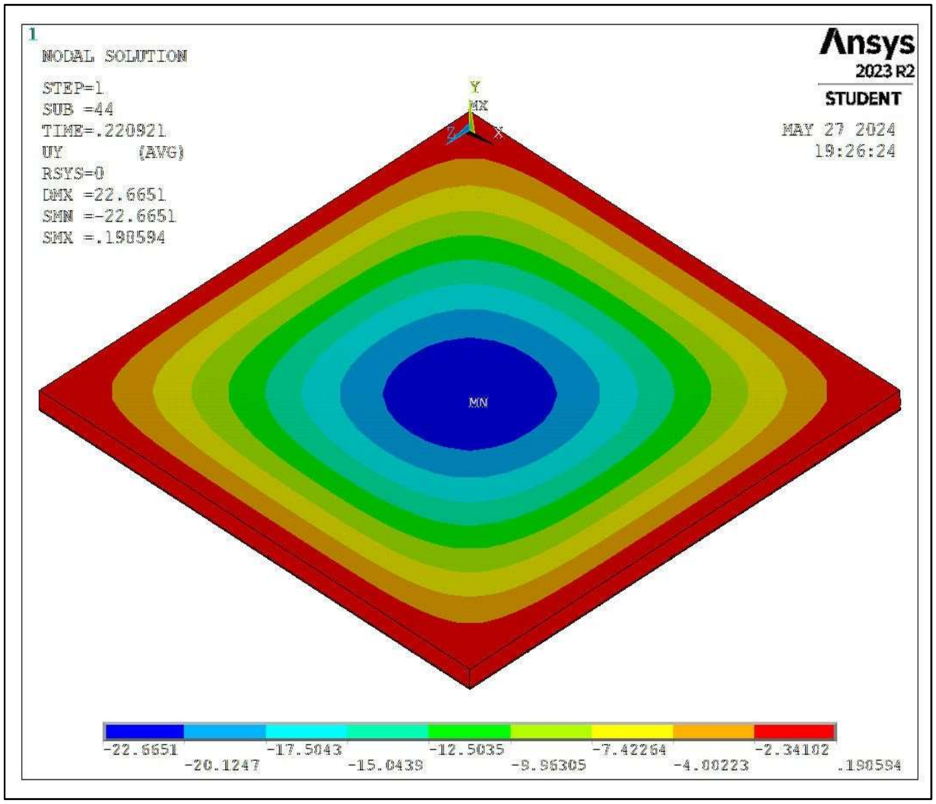


Fig. 27. Contour Plot of Deflection in Y direction of FEM Model in ANSYS

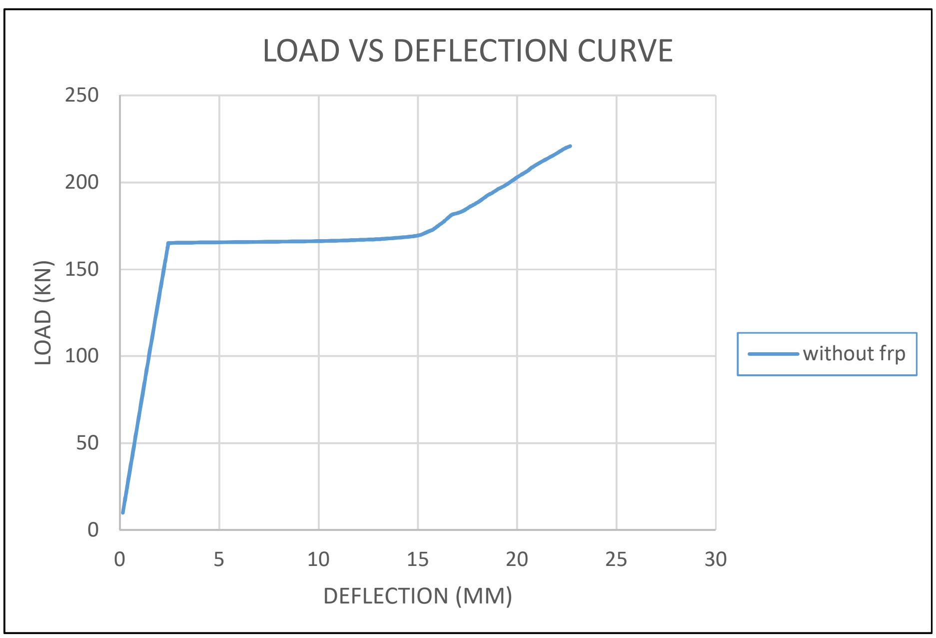


Fig. 26. Load vs Deflection curve of slab central point of FEM Model in ANSYS

This load vs deflection curve helped us to understand the variation of deflection with respect to the FRP pattern used in the next section of this chapter.

5.3. Analysis of retrofitted slab with different location of FRP

To strengthen the basic reinforced concrete slab (also termed here as control slab SS1), FRP laminates are considered as attached with the bottom surface of the slab. To study the effect, four different locations of the FRP strips are considered

a) Control slab or without FRP (SS1)
b) Full length FRP strips placed along a single direction parallel to the edge at an equal interval. (SS2),
c) Full length FRP strips placed along a single diagonal direction at an equal interval. (SS3)
d) Full length FRP strips placed along mutually perpendicular direction parallel to the edge at an equal interval. (SS4).
e) Full length FRP strips placed along mutually perpendicular diagonal direction at an equal interval. (SS5).

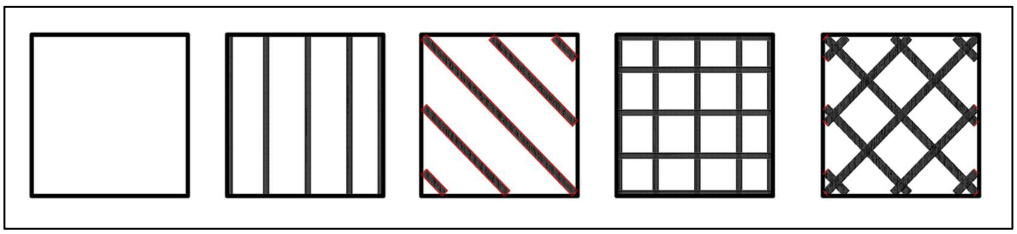


Fig. 28. a. SS11 b. SS21 c. SS31 d. SS41 e. SS51

Firstly, the variation of load deformation behaviour of retrofitted simply supported RC slab due to change in location of FRP is analysis and compared. The FRP details are given as mentioned below for this comparison:

a) SS11: No FRP used
b) SS21: 5 Nos 100 mm width full length FRP strips placed along a single direction parallel to the edge at a suitable interval, FRP strip Cover the surface of slab 16.67%
c) SS31: 5 Nos 141 mm width full length FRP strips placed along a single diagonal direction at an equal interval, FRP strip Cover the surface of slab 14.44%
d) SS41: 5 Nos 100 mm width full length FRP strips placed along mutually perpendicular direction parallel to the edge at an equal interval, FRP strip Cover the surface of slab 30.55%
e) SS51: 5 Nos 141 mm width full length FRP strips placed along mutually perpendicular diagonal direction at an equal interval, FRP strip Cover the surface of slab 27.78%

Under the Loading and boundary condition stated in chapter-3 the result computed and comparison graph is as following

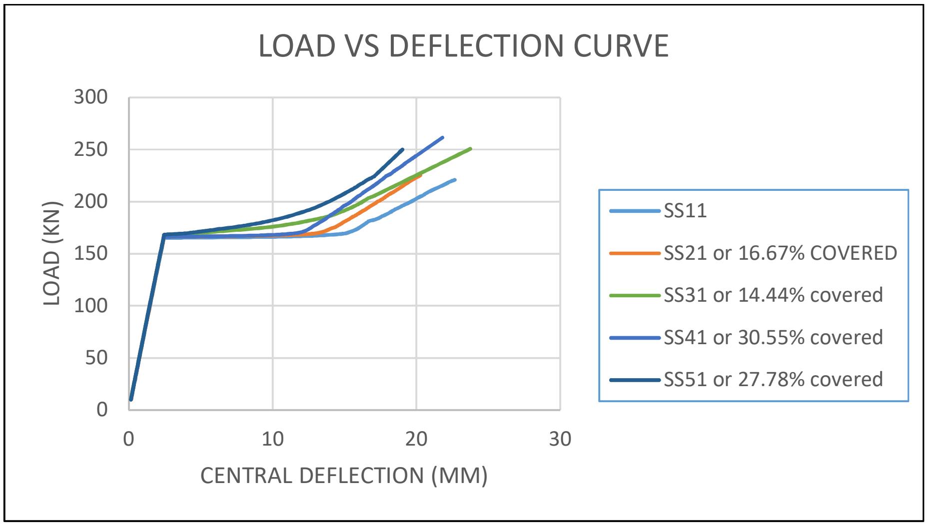


Fig. 29. Variation of load vs deformation behaviour under different location of FRP

The comparison not only shows that the slabs get more stiffer if we use the FRP strip to the diagonal direction from parallel to the edge direction. It can be observed that between SS21 and SS31 even the diagonal direction FRP strip have lesser surface area covered still it gives a higher stiffness to the slab. Similarly, it can be observed that between SS41 and SS51 even the diagonal direction FRP strip have lesser surface area covered still it gives a higher stiffness to the slab.

5.4. Analysis of retrofitted slabs with different width of FRP

The width of FRP laminate in each of the retrofitted slabs SS2, SS3, SS4 & SS5 is considered as a variable parameter in this section as this has a considerable effect on the behavior of the slab.

5.4.1. Full length FRP strips placed along a single direction parallel to the edge at a suitable interval. (SS2),

In slab SS2, the FRP has been provided parallel to the support edge in one direction at a suitable interval. But initially in the model, FRP elements are attached with the outermost elements of the model as shown in Fig. 30. Thus, the percentage of slab area covered with FRP are increased from 0% to 16.67%, 33.33%, 50%, 66.67%, 83.33% and 100% respectively. All these models are analyzed and the load-deflection plots coming from the analysis are compared as follows.

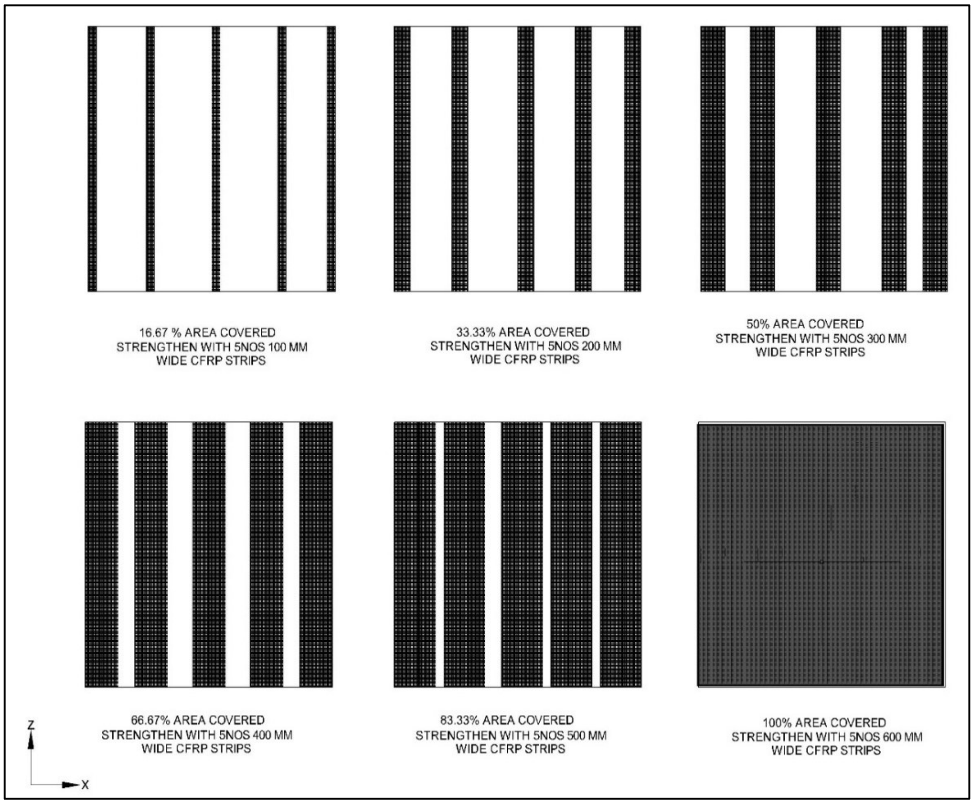


Fig. 30. Plan of FRP width variation under SS2

Labeling of different slabs with variation of FRP width under SS2:

1) SS21: 5 Nos 100 mm width full length FRP strips placed along a single direction parallel to the edge at a suitable interval, FRP strip Cover the surface of slab 16.67%
2) SS22: 5 Nos 200 mm width full length FRP strips placed along a single direction parallel to the edge at a suitable interval, FRP strip Cover the surface of slab 33.33%
3) SS23: 5 Nos 300 mm width full length FRP strips placed along a single direction parallel to the edge at a suitable interval, FRP strip Cover the surface of slab 50%
4) SS24: 5 Nos 400 mm width full length FRP strips placed along a single direction parallel to the edge at a suitable interval, FRP strip Cover the surface of slab 66.67%
5) SS25: 5 Nos 500 mm width full length FRP strips placed along a single direction parallel to the edge at a suitable interval, FRP strip Cover the surface of slab 83.33%
6) SS26: 5 Nos 600 mm width full length FRP strips placed along a single direction parallel to the edge at a suitable interval, FRP strip Cover the surface of slab 100%

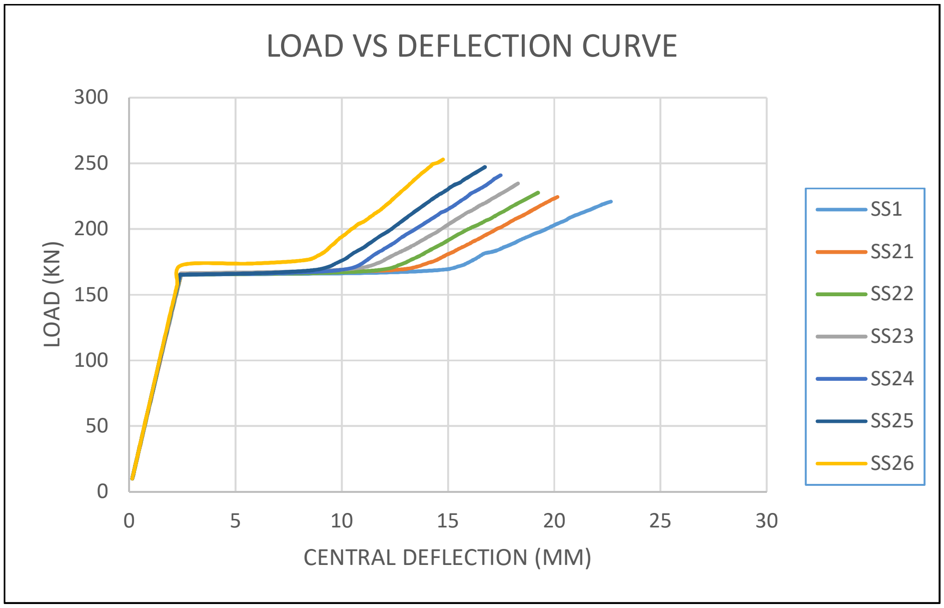


Fig. 31. Variation of load vs deformation behaviour with FRP under SS2

The comparison not only shows that the slabs get more stiffer with the increment in the area of FRP laminates but also indicates that the failure load increases with higher FRP area.

The following table shows the variation of stiffness and ultimate load carrying capacity with the increment of slab surface covered area of FRP.

Table 13. Full Length FRP Strips Placed along a Single Direction Parallel to the Edge

	Width of FRP Strip Used (MM)	% Slab surface Area Covered	Actual FRP Area Used (M^2)	Ultimate Load (KN)	% Increase of Ultimate Load Carrying Capacity	Max Deflection (MM)	% Decrease in Maximum Deflection
SS1	0	0	0	220.92	0.00	22.66	0.00
SS21	100	16.67%	1.5	225.41	2.03	20.27	10.55
SS22	200	33.33%	3	227.66	3.05	19.24	15.09
SS23	300	50%	4.5	234.68	6.23	18.29	19.27
SS24	400	66.67%	6	240.93	9.06	17.48	22.87
SS25	500	83.33%	7.5	247.21	11.90	16.74	26.13
SS26	FULL	100%	9	252.93	14.49	14.76	34.84

Now if we plot this variation of % Increase of Ultimate Load Carrying Capacity with respect to % of area covered with FRP the we get a curve showing in the following graph

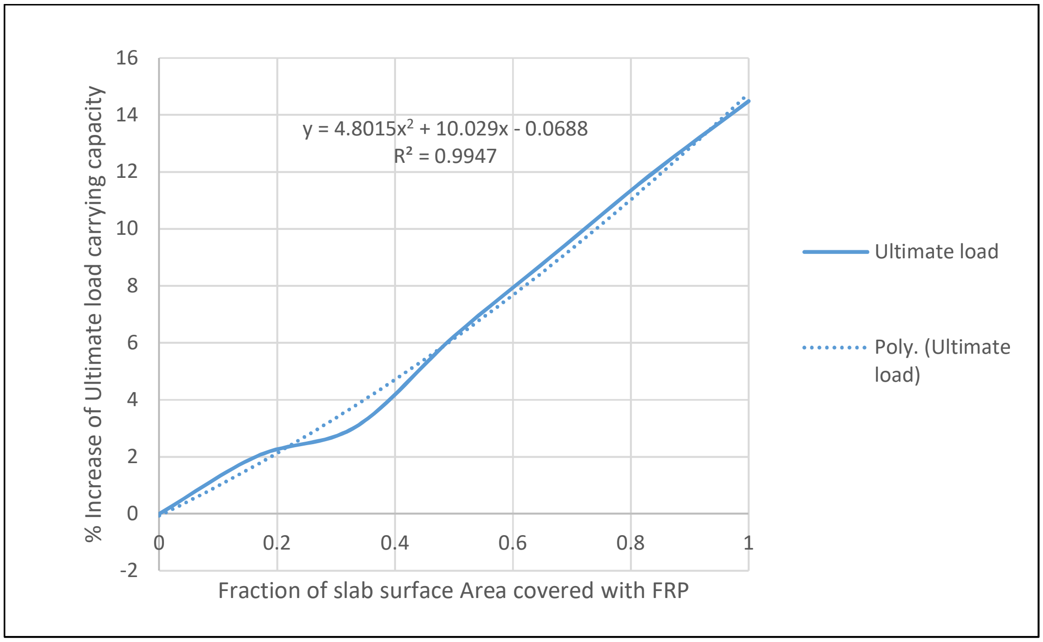


Fig. 32. % Increase of Ultimate load carrying capacity vs Area covered with FRP

The approximate polynomial equation of second order we evaluated form the above variation curve can be used for practical implementation.

$$\mathbf{y = 4.8015x^2 + 10.029x - 0.0688}$$

In the above equation **y represent the % Increase of Ultimate load carrying capacity** and **x represent Fraction of slab surface Area covered with FRP**. Being of negligible amount the constant part of the equation may be omitted while using the equation for practical purpose.

Now if we plot this variation of % Decrease in Maximum Deflection with respect to % of surface area covered with FRP the we get a curve showing in the following graph.

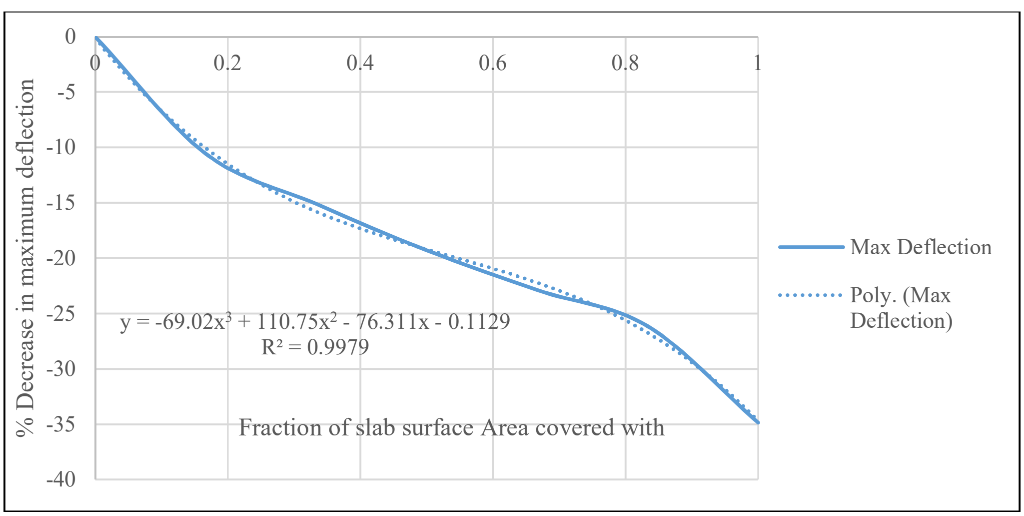


Fig. 33. % Decrease in maximum deflection vs Area covered with FRP\

The approximate polynomial equation of third order we evaluated form the above variation curve can be used for practical implementation.

$$\mathbf{y = -69.02x^3 + 110.75x^2 - 76.311x - 0.1129}$$

In the above equation y represent the % Decrease in maximum deflection and x represent Fraction of slab surface Area covered with FRP. Being of negligible amount the constant part of the equation may be omitted while using the equation for practical purpose.
This above 2 equations are only applicable if the retrofitting pattern is predetermined to be used as full length FRP strips placed along a single direction parallel to the edge at a suitable interval (SS2).

5.4.2. Full length FRP strips placed along a single diagonal direction at a suitable interval. (SS3)

In slab SS3, the FRP has been provided diagonally in one direction at a suitable interval. But initially in the model, FRP elements are attached with the outermost elements of the model. Thus, the percentage of slab area covered with FRP are increased from 0% to 14.44%, 30.21%, 46.87%, 65.76%, 81.54% and 100% respectively. All these models are analyzed and the load-deflection plots coming from the analysis are compared as shown below.

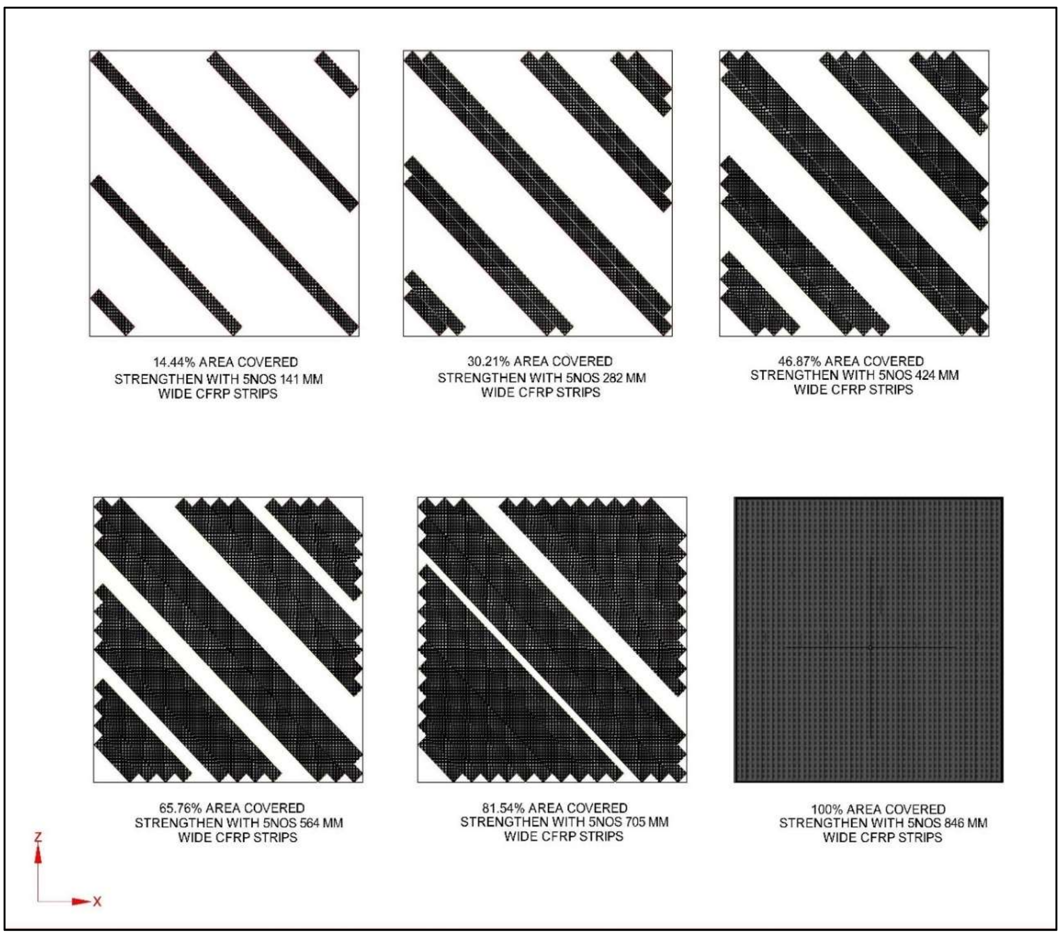


Fig. 34. Plan of FRP width variation under SS3

Labeling of different slabs with variation of FRP width under SS3:

1) SS31: 5 Nos 141 mm width full length FRP strips placed along a single diagonal direction at a suitable interval, FRP strip Cover the surface of slab 14,44%
2) SS32: 5 Nos 282 mm width full length FRP strips placed along a single diagonal direction at a suitable interval, FRP strip Cover the surface of slab 30.21%
3) SS33: 5 Nos 424 mm width full length FRP strips placed along a single diagonal direction at a suitable interval, FRP strip Cover the surface of slab 46.87%
4) SS34: 5 Nos 564 mm width full length FRP strips placed along a single diagonal direction at a suitable interval, FRP strip Cover the surface of slab 65.76%
5) SS35: 5 Nos 705 mm width full length FRP strips placed along a single diagonal direction at a suitable interval, FRP strip Cover the surface of slab 81.54%
6) SS36: 5 Nos 846 mm width full length FRP strips placed along a single diagonal direction at a suitable interval, FRP strip Cover the surface of slab 100%

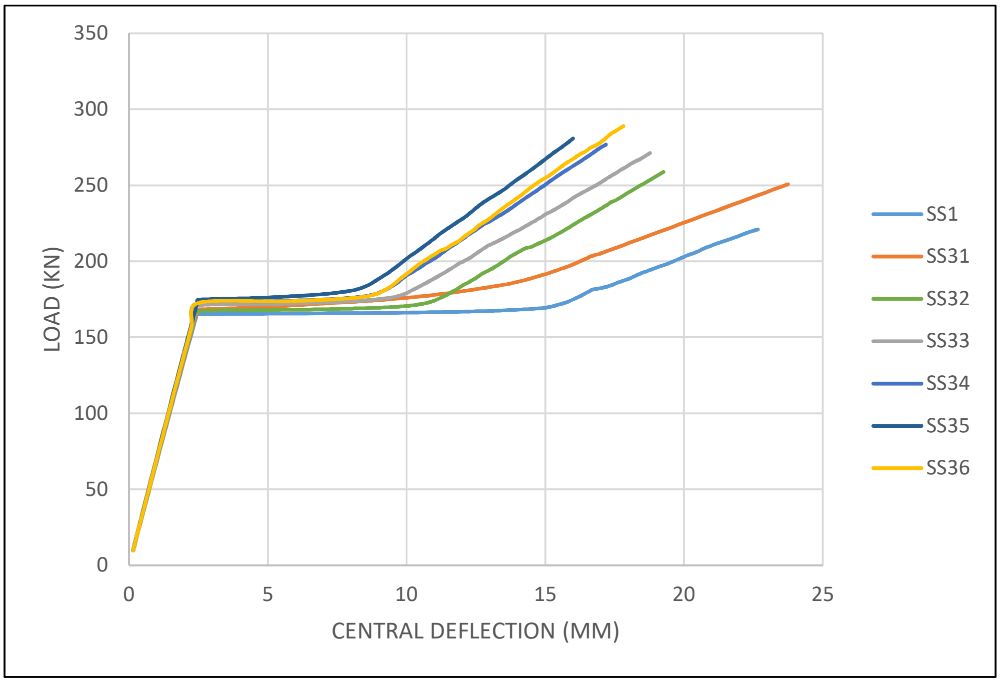


Fig. 35. Variation of load vs deformation behaviour with FRP under SS3

The comparison not only shows that the slabs get more stiffer with the increment in the area of FRP laminates but also indicates that the failure load increases with higher FRP area.
The following Table shows the variation of stiffness and ultimate load carrying capacity with the increment of slab surface covered area of FRP.

Table 14. Full length FRP strips placed along a single diagonal direction at an equal interval.

	Width of FRP Strip Used (MM)	% Slab surface Area Covered	Actual FRP Area Used (M^2)	Ultimate Load (KN)	% Increase of Ultimate Load Carrying Capacity	Max Deflection (MM)	% Decrease in Maximum Deflection

SS1	0	0	0	220.92	0.00	22.66	0.00
SS31	141	14.44%	1.3	250.68	13.47	20.01	-11.71
SS32	282	30.21%	2.72	258.79	17.14	19.63	-13.39
SS33	424	46.87%	4.22	271.14	22.73	18.77	-17.17
SS34	564	65.76%	5.92	276.79	25.29	17.19	-24.17
SS35	705	81.54%	7.34	280.75	27.08	16.00	-29.42
SS36	FULL	100%	9	288.86	30.75	15.23	-32.80

Now if we plot this variation of ultimate load carrying capacity with respect to area covered with FRP the we get a curve showing in the following graph.

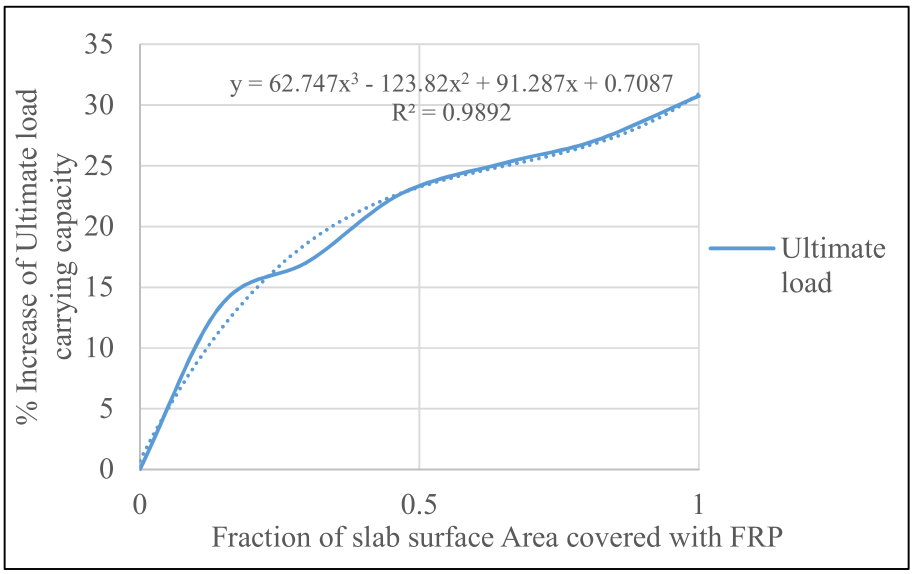


Fig. 36. % increment of Ultimate load carrying capacity vs Area covered with FRP

The approximate polynomial equation of third order we evaluated form the above variation curve can be used for practical implementation.

$$\mathbf{y = 62.747x^3 - 123.82x^2 + 91.287x + 0.7087}$$

In the above equation y represent the % Increase of Ultimate load carrying capacity and x represent Fraction of slab surface Area covered with FRP. Being of negligible amount the constant part of the equation may be omitted while using the equation for practical purpose.

Now if we plot this variation of Maximum Deflection with respect to area covered with FRP the we get a curve showing in the following graph

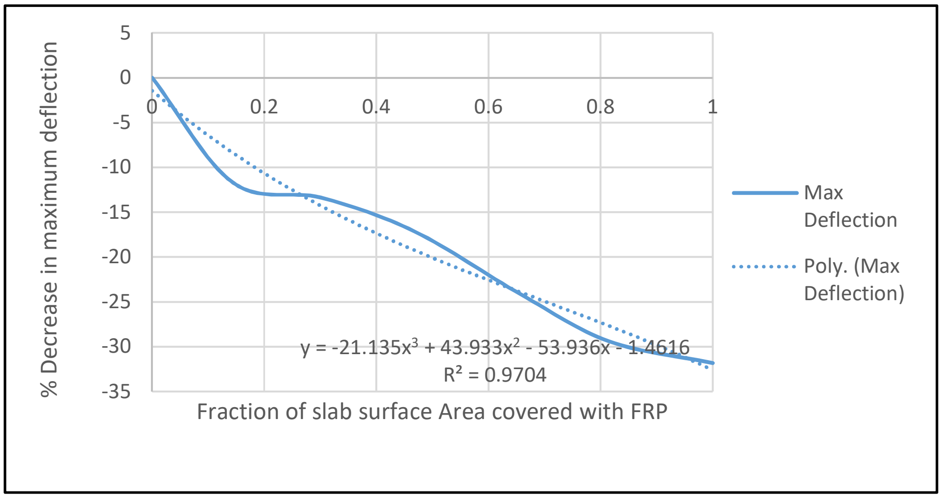


Fig. 37. % Decrease in maximum deflection vs Area covered with FRP

The approximate polynomial equation of third order we evaluated form the above variation curve can be used for practical implementation.

$$\mathbf{y = -21.135x^3 + 43.933x^2 - 53.936x - 1.4616}$$

In the above equation y represent the % Decrease in maximum deflection and x represent Fraction of slab surface Area covered with FRP. Being of negligible amount the constant part of the equation may be omitted while using the equation for practical purpose.

This above 2 equations are only applicable if the retrofitting pattern is predetermined to be used as full length FRP strips placed along a single diagonal direction at an equal interval (SS3).

5.4.3. Full length FRP strips placed along mutually perpendicular direction parallel to the edge at a suitable interval. (SS4).

In slab SS4, the FRP has been provided along mutually perpendicular direction parallel to the edge at a suitable interval. But initially in the model, FRP elements are attached with the outermost elements of the model. Thus, the percentage of slab area covered with FRP are increased from 0% to 30.55%, 55.55%, 75%, 88.89%, 97.22% and 100% respectively. All these models are analyzed and the load-deflection plots coming from the analysis are compared as shown below

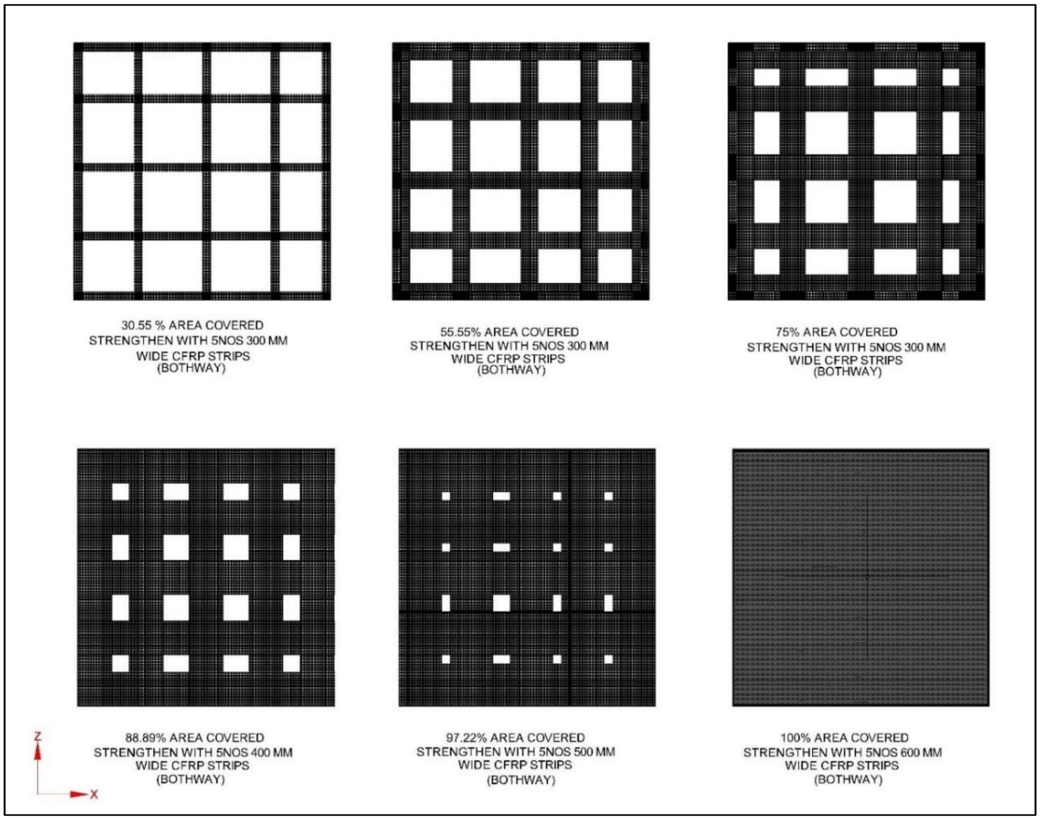


Fig. 38. Plan of FRP width variation under SS4

Labeling of different slabs with variation of FRP width under SS4:

1) SS41: 5 Nos 100 mm width full length FRP strips placed along mutually perpendicular direction parallel to the edge at a suitable interval, FRP strip Cover the surface of slab 30.55%
2) SS42: 5 Nos 200 mm width full length FRP strips placed along mutually perpendicular direction parallel to the edge at a suitable interval, FRP strip Cover the surface of slab 55.55%
3) SS43: 5 Nos 300 mm width full length FRP strips placed along mutually perpendicular direction parallel to the edge at a suitable interval, FRP strip Cover the surface of slab 75%
4) SS44: 5 Nos 400 mm width full length FRP strips placed along mutually perpendicular direction parallel to the edge at a suitable interval, FRP strip Cover the surface of slab 88.89%

5) SS45: 5 Nos 500 mm width full length FRP strips placed along mutually perpendicular direction parallel to the edge at a suitable interval, FRP strip Cover the surface of slab 97.22%

6) SS46: 5 Nos 600 mm width full length FRP strips placed along mutually perpendicular direction parallel to the edge at a suitable interval, FRP strip Cover the surface of slab 100% (2 layers).

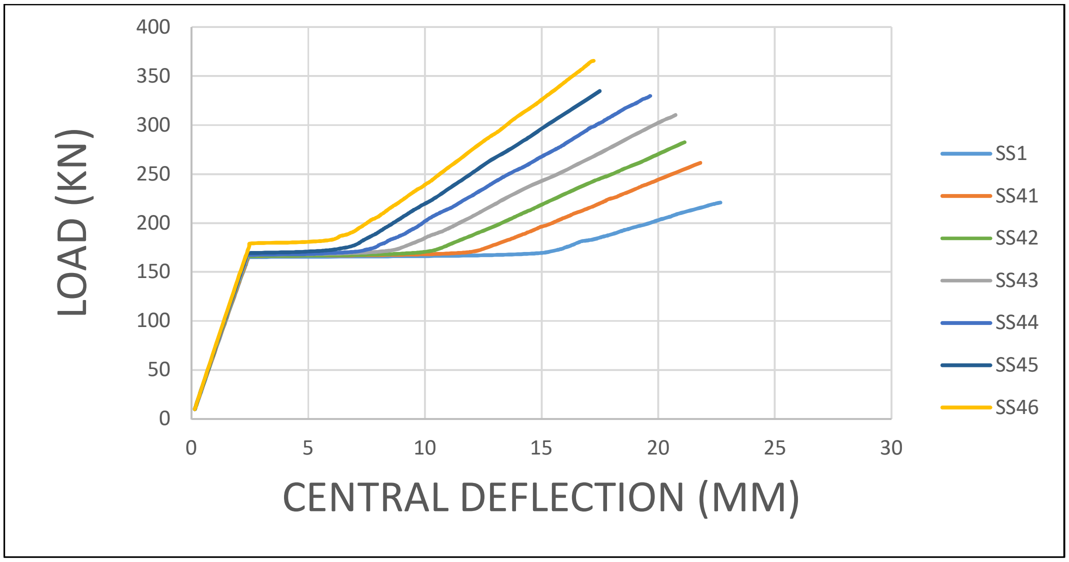


Fig. 39. LOAD VS DEFLECTION CURVE

The comparison not only shows that the slabs get more stiffer with the increment in the area of FRP laminates but also indicates that the failure load increases with higher FRP area. The following Table shows the variation of stiffness and ultimate load carrying capacity with the increment of slab surface covered area of FRP.

Table 15. Full length FRP strips placed along mutually perpendicular direction parallel to the edge

	Width of FRP Strip Used (MM)	% Slab surface Area Covered	Actual FRP Area Used (M^2)	Ultimate Load (KN)	% Increase of Ultimate Load Carrying Capacity	Max Deflection (MM)	% Decrease in Maximum Deflection
SS1	0	0	0	220.92	0.00	22.66	0.00
SS41	100	30.55%	3	261.52	18.38	21.80	-3.79
SS42	200	55.55%	6	282.52	27.88	21.13	-6.79
SS43	300	75%	9	310.39	40.50	20.74	-8.49
SS44	400	88.89%	12	329.75	49.26	19.66	-13.27
SS45	500	97.22%	15	334.86	51.57	17.49	-22.81
SS46	600	100%	18	365.74	65.55	17.23	-23.97

Now if we plot this variation of ultimate load carrying capacity with respect to area covered with FRP the we get a curve showing in the following graph

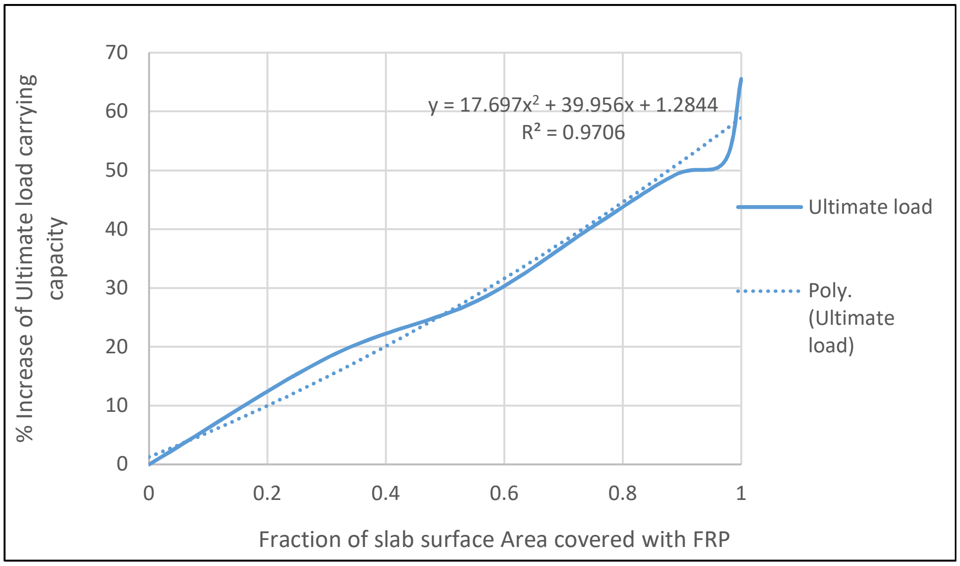


Fig. 40. % increment of Ultimate load carrying capacity vs Area covered with FRP

The approximate polynomial equation of second order we evaluated form the above variation curve can be used for practical implementation.

$$\mathbf{y = 17.697x^2 + 39.956x + 1.2844}$$

In the above equation y represent the % Increase of Ultimate load carrying capacity and x represent Fraction of slab surface Area covered with FRP. Being of negligible amount the constant part of the equation may be omitted while using the equation for practical purpose.

Now if we plot this variation of Maximum Deflection with respect to area covered with FRP the we get a curve showing in the following graph

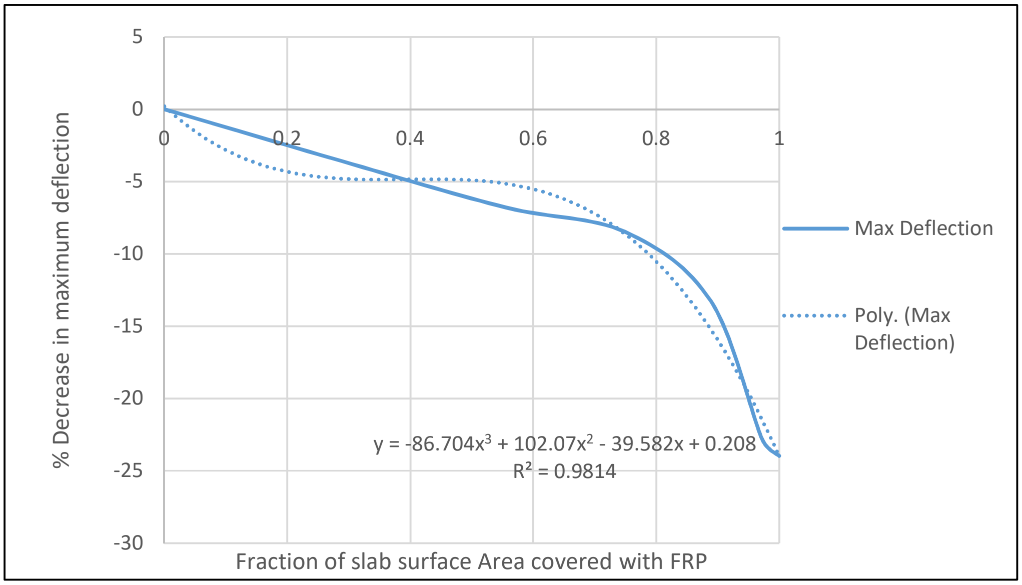


Fig. 41. % Decrease in maximum deflection vs Area covered with FRP

The approximate polynomial equation of third order we evaluated form the above variation curve can be used for practical implementation.

$$\mathbf{y = -86.704x^3 + 102.07x^2 - 39.582x + 0.208}$$

In the above equation y represent the % Decrease in maximum deflection and x represent Fraction of slab surface Area covered with FRP. Being of negligible amount the constant part of the equation may be omitted while using the equation for practical purpose.

This above 2 equations are only applicable if the retrofitting pattern is predetermined to be used as full length FRP strips placed along mutually perpendicular direction parallel to the edge at a suitable interval (SS4).

5.4.4. Full length FRP strips placed along mutually perpendicular diagonal direction at a suitable interval. (SS5).

In slab SS5, the FRP has been provided along mutually perpendicular diagonal direction at a suitable interval. But initially in the model, FRP elements are attached with the outermost elements of the model. Thus, the percentage of slab area covered with FRP are increased from 0% to 27.78%, 50%, 70.55%, 83.52%, 93.33% and 100% respectively. All these models are analyzed and the load-deflection plots coming from the analysis are compared as shown below:

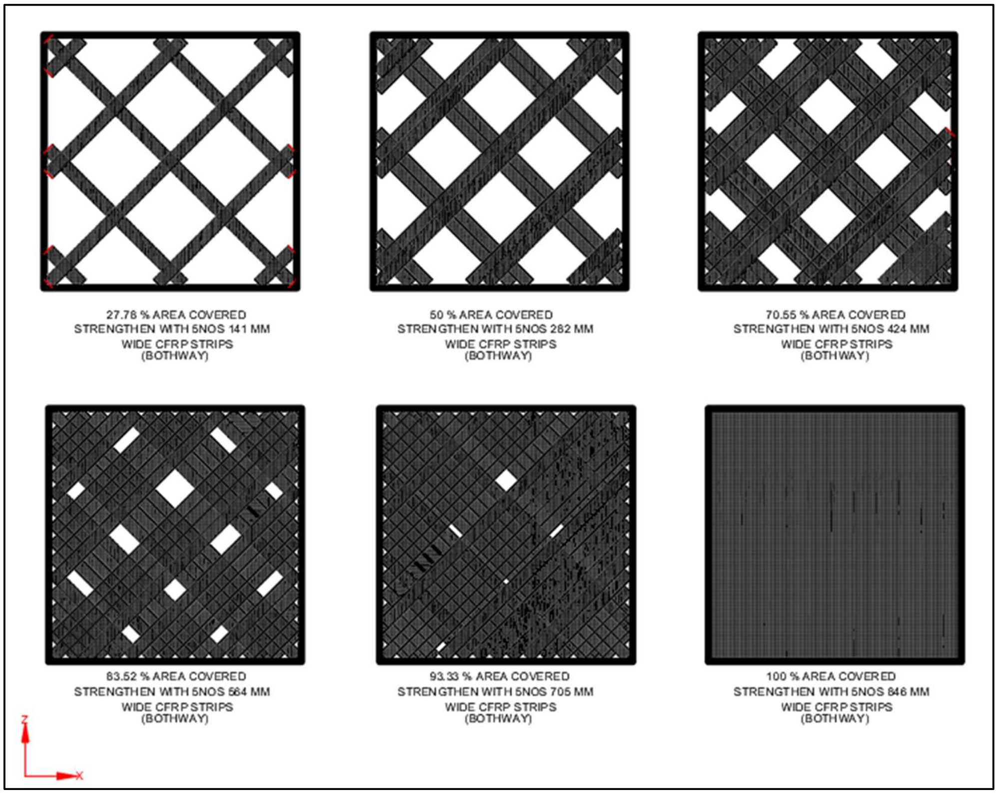


Fig. 42. Plan of FRP width variation under SS5

Labeling of different slabs with variation of FRP width under SS5:

1) SS51: 5 Nos 141 mm width full length FRP strips placed along mutually perpendicular diagonal direction at a suitable interval, FRP strip Cover the surface of slab 27.78%
2) SS52: 5 Nos 282 mm width full length FRP strips placed along mutually perpendicular diagonal direction at a suitable interval, FRP strip Cover the surface of slab 50%
3) SS53: 5 Nos 424 mm width full length FRP strips placed along mutually perpendicular diagonal direction at a suitable interval, FRP strip Cover the surface of slab 70.55%
4) SS54: 5 Nos 564 mm width full length FRP strips placed along mutually perpendicular diagonal direction at a suitable interval, FRP strip Cover the surface of slab 83.52%
5) SS55: 5 Nos 705 mm width full length FRP strips placed along mutually perpendicular diagonal direction at a suitable interval, FRP strip Cover the surface of slab 93.33%
6) SS56: 5 Nos 846 mm width full length FRP strips placed along mutually perpendicular diagonal direction at a suitable interval, FRP strip Cover the surface of slab 100% (2 layers).

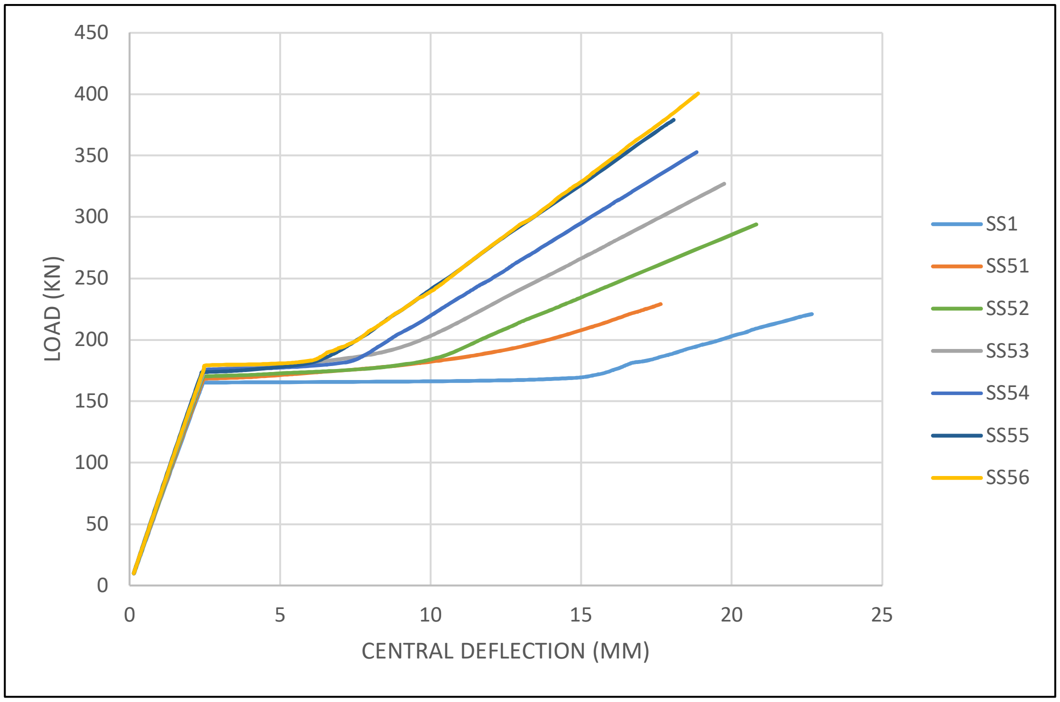


Fig. 43. Variation of load vs deformation behaviour with FRP under SS5

The comparison not only shows that the slabs get more stiffer with the increment in the area of FRP laminates but also indicates that the failure load increases with higher FRP area.

The following Table shows the variation of stiffness and ultimate load carrying capacity with the increment of slab surface covered area of FRP.

Table 16. Full length FRP strips placed along mutually perpendicular diagonal direction

	Width of FRP Strip Used (MM)	**% Slab surface Area Covered**	**Actual FRP Area Used (M^2)**	**Ultimate Load (KN)**	**% Increase of Ultimate Load Carrying Capacity**	**Max Deflection (MM)**	**% Decrease in Maximum Deflection**
SS1	0	0	0	220.92	0.00	22.66	0.00
SS51	141	27.78%	2.6	250.02	13.17	21.71	-4.21
SS52	282	50.00%	5.44	293.96	33.06	20.8175	-8.15
SS53	424	70.55%	8.44	327.08	48.05	19.75	-12.85
SS54	564	83.52%	11.84	352.8290	59.71	18.8319	-16.91
SS55	705	93.33%	14.68	379.0234	71.57	18.07	-20.25
SS56	FULL	100%	18	400.57	81.32	17.98	-20.66

Now if we plot this variation of ultimate load carrying capacity with respect to area covered with FRP the we get a curve showing in the following graph.

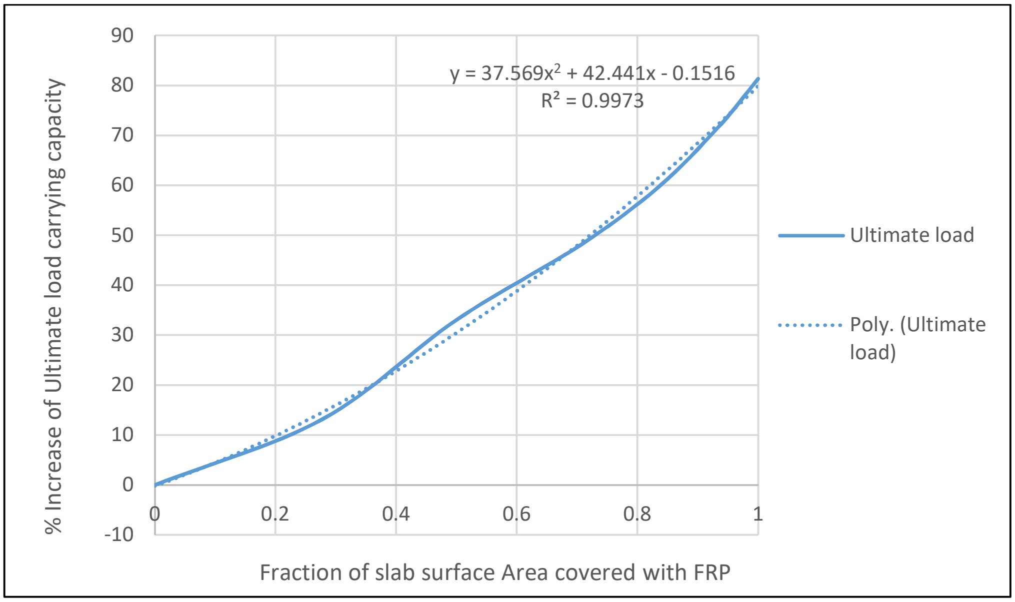


Fig. 44. % increment of Ultimate load carrying capacity vs Area covered with FRP

The approximate polynomial equation of second order we evaluated form the above variation curve can be used for practical implementation.

$$y = 37.569x^2 + 42.441x - 0.1516$$

In the above equation y represent the % Increase of Ultimate load carrying capacity and x represent Fraction of slab surface Area covered with FRP. Being of negligible amount the constant part of the equation may be omitted while using the equation for practical purpose.

Nextly, if we plot this variation of Maximum Deflection with respect to area covered

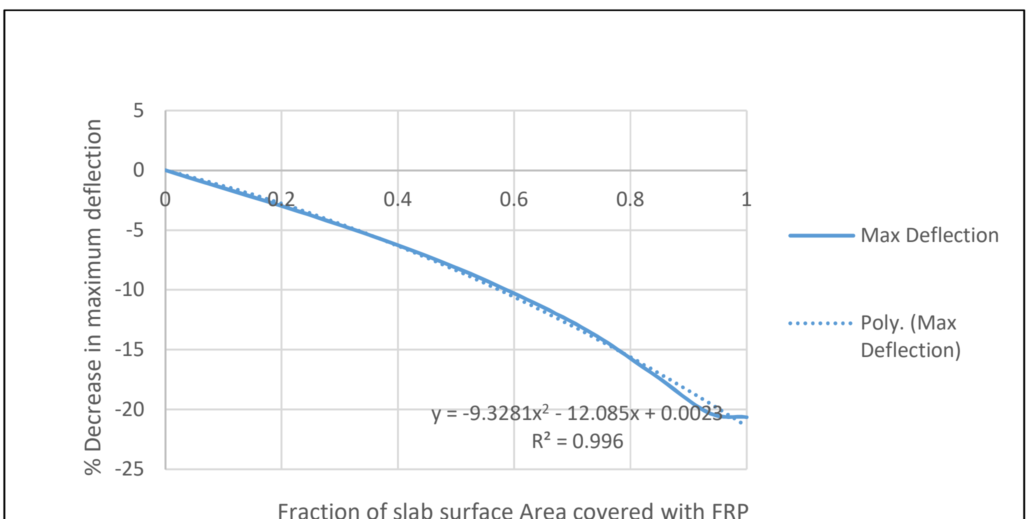


Fig. 45. % Decrease in maximum deflection vs Area covered with FRP

with FRP the we get a curve showing in the following graph

The approximate polynomial equation of second order we evaluated form the above variation curve can be used for practical implementation.

$$\mathbf{y = -9.3281x^2 - 12.085x + 0.0023}$$

In the above equation y represent the % Decrease in maximum deflection and x represent Fraction of slab surface Area covered with FRP. Being of negligible amount the constant part of the equation may be omitted while using the equation for practical purpose.
This above 2 equations are only applicable if the retrofitting pattern is predetermined to be used as full length FRP strips placed along mutually perpendicular diagonal direction at a suitable interval (SS5).

5.5 Comparison of Concrete Crack under different pattern of retrofitted slabs with FRP

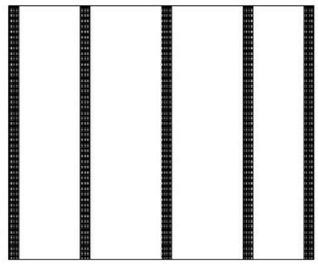
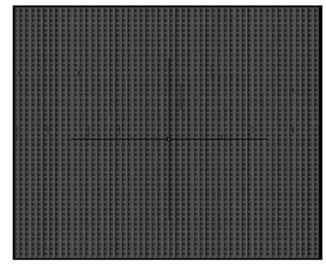
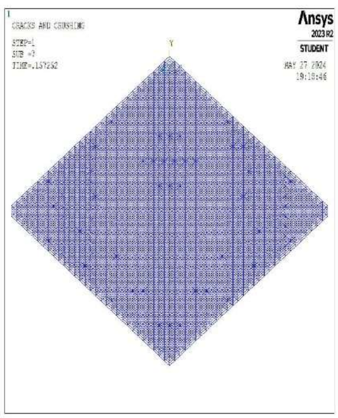
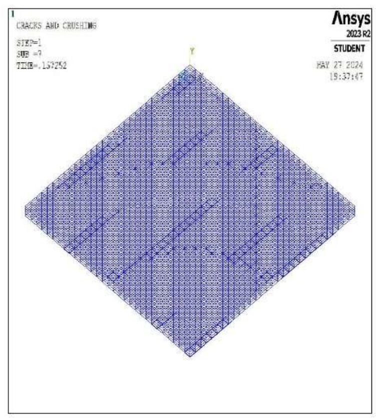
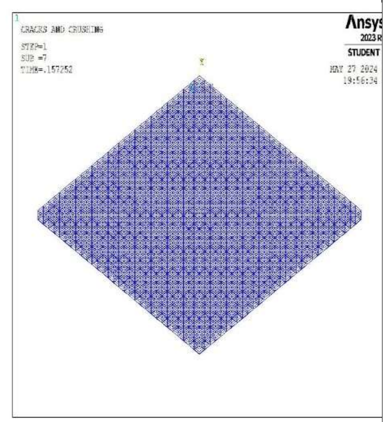
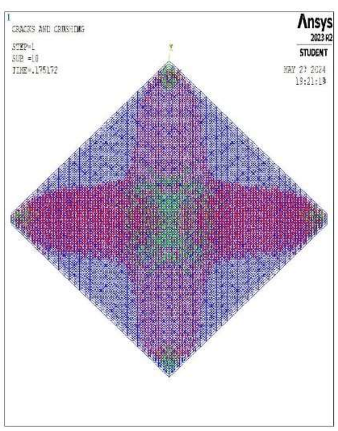
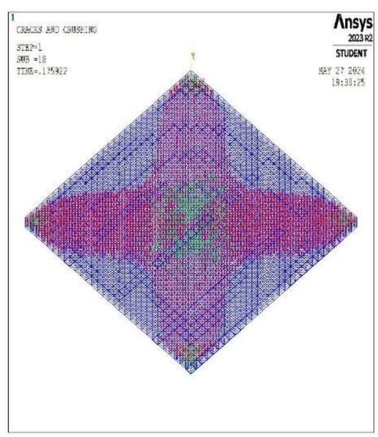
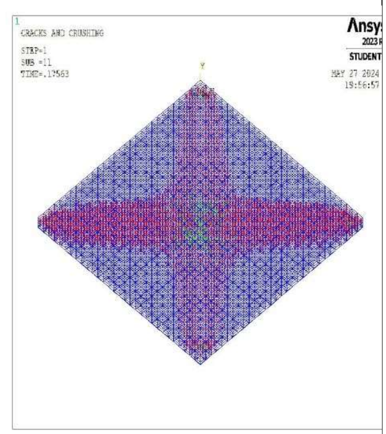
5.5.1. Comparison with increase in FRP area

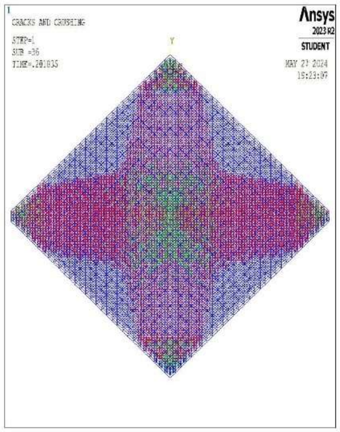
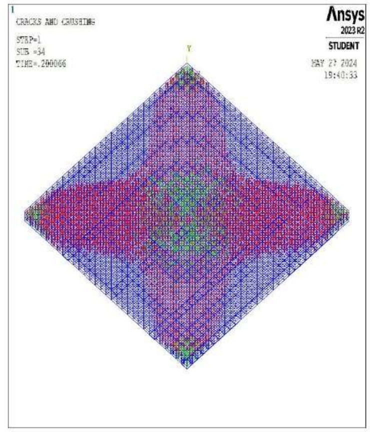
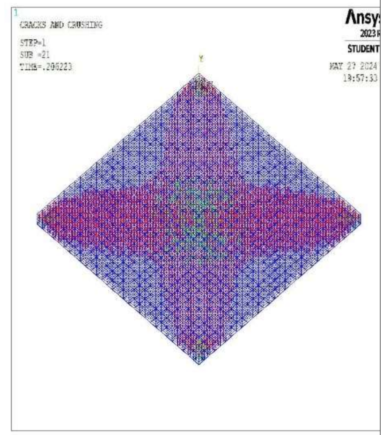
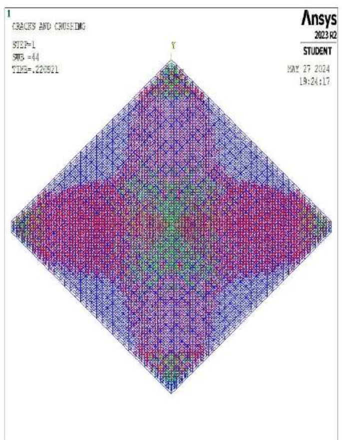
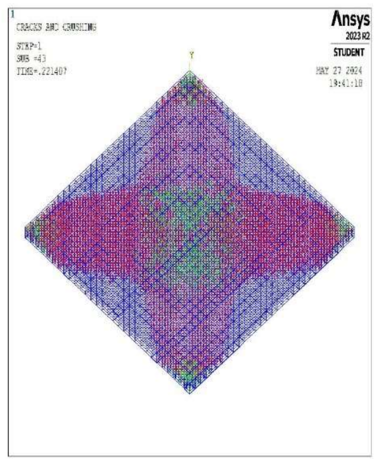
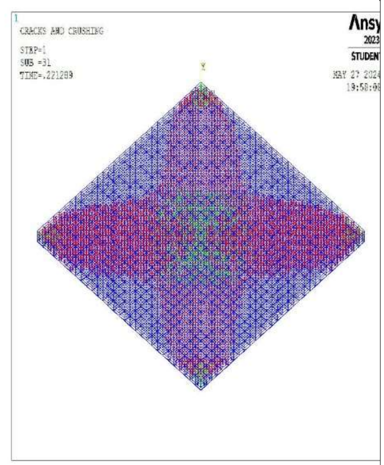
One comparison study is done for better understanding of the concrete crack generation at different loading intensity for the slabs strengthened with selected FRP retrofitting pattern which we already have mentioned in pervious sections of this chapter.

For this comparison study 4 slabs are selected which have the following retrofitting patterns

a) SS1: No FRP used
b) SS21: 5 Nos 100 mm width full length FRP strips placed along a single direction parallel to the edge at a suitable interval, FRP strip Cover the surface of slab 16.67%
c) SS26: 5 Nos 600 mm width full length FRP strips placed along a single direction parallel to the edge at a suitable interval, FRP strip Cover the surface of slab 100%
d) SS31: 5 Nos 141 mm width full length FRP strips placed along a single diagonal direction at a suitable interval, FRP strip Cover the surface of slab 14.44%

The first comparison is done between 3 slabs labeled as SS1, SS21 & SS26 to check if the any change in the concrete crack generation at different load intensity level. The comparison pictures are shown in the following table.

	SS1	SS21	SS26
Retrofitting pattern			
150 KN			
175 KN			

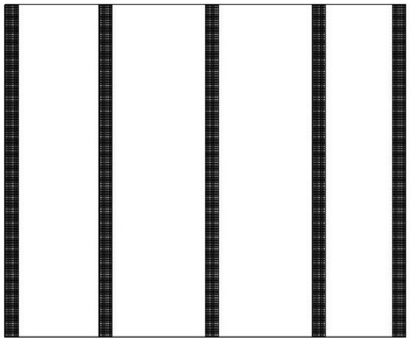
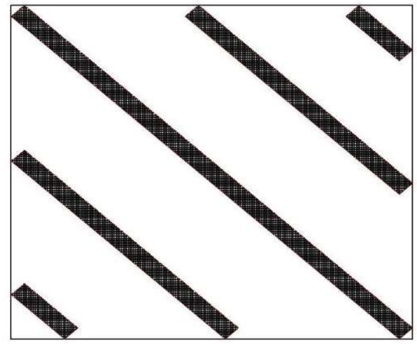
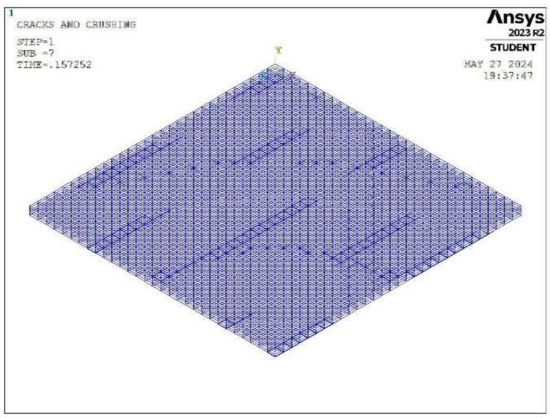
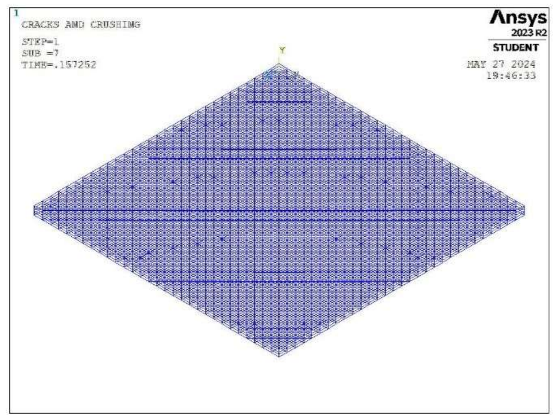
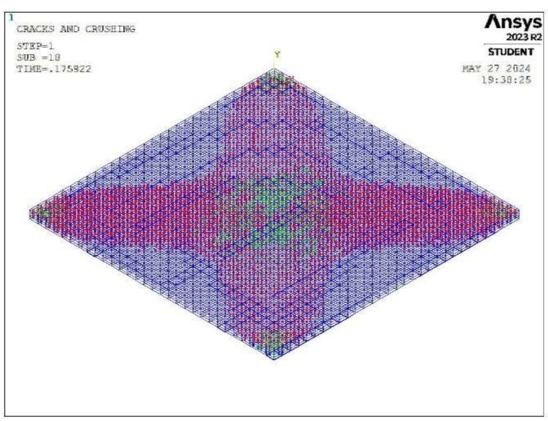
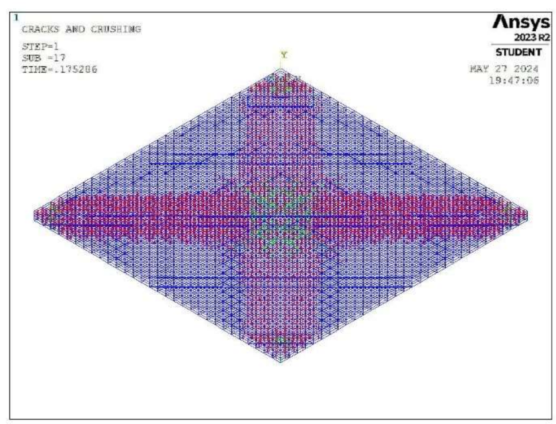
200 KN			
220 KN			

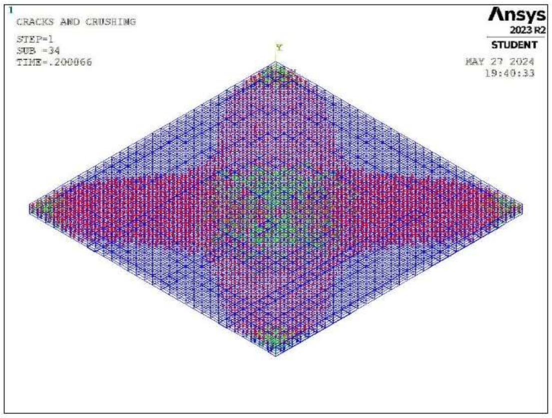
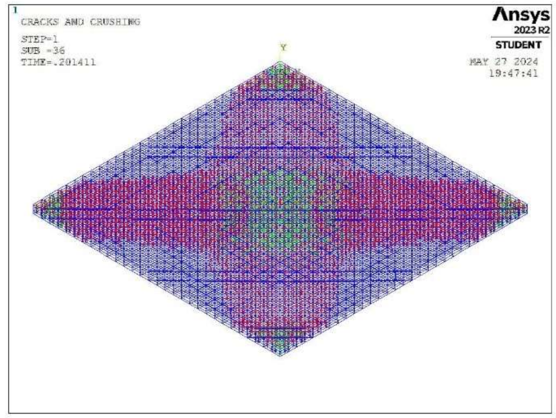
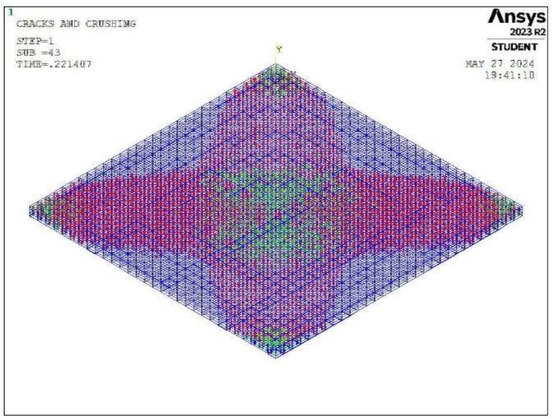
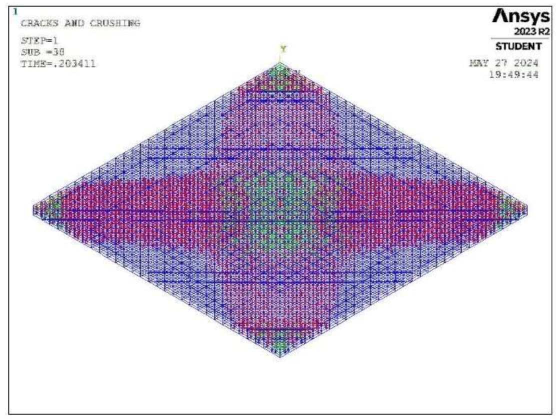
From the above table by visualizing it can be observed that as the FRP coverage area increases the concrete crack generation decreases. In the above pictures, magenta color represents first crack and green color represent second crack.

It also can be understood that the crack generates along the diagonal line of the slab with the increase of loading.

5.5.2. Comparison with change in FRP direction

As stated in the earlier comparison the crack generates along the diagonal line of the slab with the increase of loading that’s why in this comparison one along the edge FRP pattern (SS21) compared with one diagonal direction FRP pattern (SS31). The comparison pictures are shown in the following table.

	SS21	SS31
Retrofitting pattern		
150 KN		
175 KN		

200 KN		
220 KN		

From the above table by visualizing it can be observed that the concrete crack generation decreases if we use the FRP strips in diagonal direction (SS31) instead of parallel to the edge direction (SS21). Even though the diagonal direction FRP pattern (SS31) cover little less surface area of slab than parallel to the edge direction pattern (SS21), still its result is better in prevention of concrete crack generation.

CHAPTER 6. CONCLUSION

In the present research work, the finite element based numerical model of Reinforced concrete slab strengthened with Glass Fibre Reinforced Polymer (GFRP) laminates has been developed using the software ANSYS 2023 (R2).

In the first phase of this work the same model has been prepared without strengthening with FRP and analysed against gradually increasing uniformly distributed load under simply supported condition. The non-linear property of both concrete and steel have been simulated in the model by incorporating the material strength parameters as well as the uniaxial stress strain curve. The load displacement response of this control slab has been validated with previous numerical as well as experimental results reported by earlier researchers. The comparison shows the correctness of present numerical model in the linear elastic zone as well as in the ultimate nonlinear region, though some variations are observed when the model enters the initial non-linear zone. This numerical modelling methodologies has been further followed in the second phase of the work where a slab has been considered as strengthened with FRP strips.

While modelling the strengthened slabs, 4 different arrangements of FRP involving location & width are considered for the present study. In all 4 cases the modelling parameters required for the first phase of the work are kept same. The load displacement response of total 24 models have been plotted for comparison with the same of un-strengthened slab as well as for comparison among themselves. With the increment of the load cracking of concrete initiates and propagates over the plan area. The cracking profile of the strengthened slab as well as for control slab are also compared for selective models at specific load steps.

It has been found from the comparison of above results that

- There is enhancement of load carrying capacity and stiffness of the slab and decrease in the magnitude of deflection in the retrofitted slabs compared to the un-retrofitted slab in all situations.
- The enhancement of load carrying capacity and decrease in the deflection becomes more with the increase in the width of FRP strips in all 4 arrangements (SS2, SS3, SS4 & SS5)
- The extent of the effect of strengthening varies with the different arrangements of FRP. In the considered simply supported slab it is observed that the performance of slabs having FRP in diagonal directions (SS3 & SS5) are better than the slabs having FRP in the direction parallel to the edges (SS2 & SS4) in terms of stiffness and load carrying capacity. This observation remains valid for both FRP in single direction and FRP in mutually perpendicular direction.
- Comparing cracking pattern it has been found that portion of concrete getting cracked becomes less with the increase in the width of FRP or area of Slab

covered with FRP. This results in higher stiffness of the strengthened slab in the non-linear zone when FRP area is increased.

- As in the simply supported control slab, the cracks propagate in the diagonal directions, the arrangement of FRP in the diagonal direction become more effective resisting the development of cracks in strengthened slabs. This result is observed by comparing the cracking profile of the slab with FRP in diagonal **direction (**SS3) with the same of the slab with FRP in a direction parallel to edges (SS2) of the slab.

At the end of the present work, % increase of ultimate load carrying capacity and % decrease of central deflection have been plotted against the fraction of the surface area covered with FRP for all 4 arrangements. A predictive equation has been developed for each case that can predict the tentative % increase of ultimate load carrying capacity or % decrease of central deflection based on Fraction of the surface area covered with FRP for all 4 arrangements of FRP laminates.

REFERENCES

[1] Anil, O., Kaya, N. and Arslan, O. **Strengthening of one way rc slab with opening using CFRP strips**, Construction and Building Materials, 48, 883-893, 2013

[2] Belakhdar K., **Nonlinear Finite Element Analysis of reinforced concrete slab strengthened with shear bolts,** Jordan Journal of Civil Engineering, Volume 2, No. 1, 2008

[3] Ebead U.A. and Marzouk H., **Strengthening of Two-Way Slabs Subjected to Moment and Cyclic Loading**, ACI Structural Journal, V. 99, No. 4, July-August 2002

[4] Ebead U. A., Marzouk H. and Lye L. M., **Strengthening of two-way Slabs using FRP materials: a simplified analysis based on response surface methodology,** 2nd World Engineering Congress, Sarawak, Malaysia, 22-25 July 2002

[5] Ebead U. A. and Marzouk H., **ACI code verification for FRP externally reinforced slab**, ACI-440F, Conference Paper, January 2003

[6] Ebead U.A. and Marzouk H., **Fibre-Reinforced Polymer Strengthening of Two-Way Slabs**, ACI Structural Journal, V. 101, No. 5, 2004

[7] Ebead U.A. and Marzouk H., **Tension-stiffening model for FRP-strengthened RC concrete two-way slabs**, Materials and Structures, 38, 193-200, 2005

[8] Fathelbab F. A., Ramadan M. S. and Tantawy A. A., **Strengthening of RC bridge slabs using CFRP sheets**, Alexandria Engineering Journal, 53, 843–854, 2014

[9] Gawas S and Itti S.V., **Study on two way RC slab using ANSYS with and without central opening,** International Journal of Scientific Engineering and Technology, Vol.3, Issue No.8, pp: 1108-1110, 2014

[10] Limam, O., Foret, G. and Ehrlacher, A., **RC two-way slabs strengthened with CFRP strips: experimental study and a limit analysis approach**, Composite Structures 60(4), 467-471, 2003

[11] Mosallam A. S. and Mosalam K. M., **Strengthening of two-way concrete slabs with FRP composite laminates**, Construction and Building Materials, v17, 43–54, 2003

[12] Neale K.W., Ebead U.A., Baky H. M. A., Elsayed W.E., Godat A., **Modelling of Debonding Phenomena in FRP-Strengthened Concrete Beams and Slabs**, Proceedings of the International Symposium on Bond Behaviour of FRP in Structures (BBFS 2005), pp 45-54, International Institute for FRP in Construction, 2005

[13] Neale K. W., Godat A., Baky H. M. A., Elsayed W. E. and Ebead U. A., **Approaches for Finite Element simulation of FRP-strengthened concrete beam and slabs,** Architecture Civil Engineering Environment , No. 4, 2011

[14] Owen, D.R.J., J.A.Figueiras, and Damjanic, F., **Finite element analysis of reinforced and prestressed concrete structure including thermal loading**, Computer Methods in Applied Mechanics and Engineering, v.41, pp.323-366, 1983

[15] Shit F. and Roychowdhury S., A Numerical Study on the Behaviour of Reinforced Concrete Slab Strengthened with FRP Laminates Using Finite Element Approach, Recent Advances in Structural Engineering, Volume 2, Lecture Notes in Civil Engineering 12, 675-686, 2019

[16] Smith S.T. and RJ. Gravina, **Critical debonding length in FRP flexurally strengthened RC member,** Proceedings of the International Symposium on Bond Behaviour of FRP in Structures (BBFS 2005), International Institute for FRP in Construction, pp.277-282, 2005

[17] Tanu, Kaur I. and Singh Y., **Finite Element Analysis of RC Slab with or without Opening Strengthened with FRP Wraps**, International Journal of Computer Applications, International Conferences on Advances in Emerging Technologies (ICAET 2016), pp.9-12, 2016

[18] ANSYS User’s Manual, Release 23.0. (2023)