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Finite Element Modelling and Parametric Analysis of Thin Reinforced Concrete Slabs Strengthening by CFRP Laminates

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Abstract: *In this study, a non-linear three-dimensional finite element model was developed to study the flexural performance of thin reinforced concrete (RC) slabs externally strengthened with carbon fiber-reinforced polymer (CFRP) laminates at their soffit. Based on the results obtained from [1] study, a numerical model has been developed in my study to validate the experimental results through nonlinear finite element software ABAQUS [2]. The concrete damage plasticity model was used for the concrete part, a traction-separation law for the CFRP-concrete interface. A detailed parametric analysis was performed to understand the various factors affecting the CFRP strengthened Slab. The parameters used for the study include compressive strength of concrete, use of transverse laminate of CFRP, different flexural steel reinforcement ratios, and the number of layers of CFRP.*

Keywords: *strengthening, concrete slab, finite element analysis, ABAQUS, debonding.*

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I. Introduction

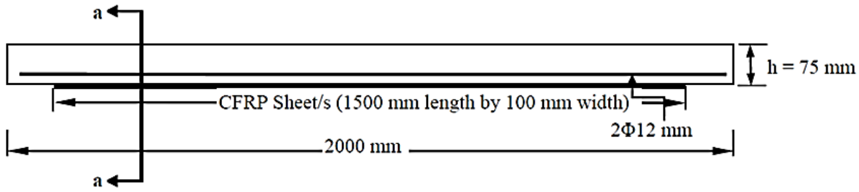
As the world's population grows, high-rise building technology allows people to live in close quarters without using large amounts of land. The subject of construction materials has risen in complexity and uses in recent years. As a result, a wide range of materials has been developed and adapted for practically any application. Fiber-reinforced polymer (FRP) composite materials are one of the most important technologies produced in the construction materials area. FRP materials are widely utilized to repair, strengthen, and rehabilitate structures in the form of sheets or bars. Depending on the nature and level of structural damage, several materials could be employed for strengthening. Fires, earthquakes, terrorist attacks, wear and tear, and changes in occupancy can all cause structural damage. Each form of damage should be examined and investigated in order to determine the best techniques for repair and strengthening. The literature on the flexural and shear behaviour of RC elements reinforced with FRP materials under various schemes is summarized in [3]. [3] also looked at the efficiency of several types of FRP materials and procedures. It also shows a cost comparison of various strengthening techniques as well as the limitations of FRP reinforcement. Changing the width and thickness of the FRP laminate was examined by [4] to investigate the behaviour of the FRP-concrete interface and the impact of various variables on the binding behaviour of FRP and concrete surfaces. Externally bonding FRP composite sheets and plates to concrete surfaces is one of the most regularly utilized methods to strengthen RC structural elements such as slabs, beams, columns, and walls in shear and flexure [5-6]. FRP strengthening systems have proven to have significant advantages over steel alternatives [7]. FRP systems have also shown a number of advantages over traditional strengthening methods, including the ability to: be easy to install and insulate, have a low maintenance cost, improved structural bonding, a high strength-to-weight ratio, and require fewer laborers to install. Engineers and academics have done numerous studies to optimize this technology as its range of applications has expanded. Bonding these polymers to the exterior surface of the reinforced concrete elements can significantly improve the performance and increase the capacity of the RC members [8-20].

Work Objective

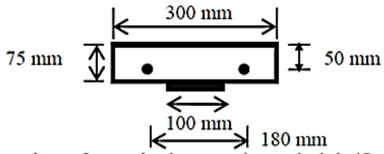
However, after reviewing prior literature and published studies, the author discovered a void in the literature discussing the flexible strengthening of high-strength thin slabs with CFRP sheets. As a result, the goal of this research is to close that gap and propose further research on the subject.

II. Summary of Experimental Program

[1] investigated the flexural performance of thin RC slabs with concrete compressive strengths of 50 and 100 MPa that were externally reinforced on the tension side with CFRP laminates. Six specimens were used in the experiment: three for compressive strength of 50 MPa (7.54 ksi) and three for compressive strength of 100 MPa (14.5 ksi). A control slab and two strengthened slabs made up the three 50 Mpa (7.54 ksi) specimens. One and two layers of CFRP laminates were used in the two strengthened slabs, respectively. The cast specimens were 2000 (78.7), 1700 (66.9), 300 (11.81), and 75 (3) mm (in.) in length, span length, breadth, and height, respectively. Two 12 mm diameter steel bars were installed at a depth of 50 mm from the slab's top surface. The specimen's details are shown in Fig.1.



a) Front view of the strengthened slab specimens



b) Cross-section of a typicalstrengthened slab (Section a-a)

Fig.1: R.C. slab specimens detailing [1].

As shown in Fig. 2, [1] performed a four-point bending test on all of the specimens. The test's results were provided in this study and the results were displayed using load versus displacement curves.

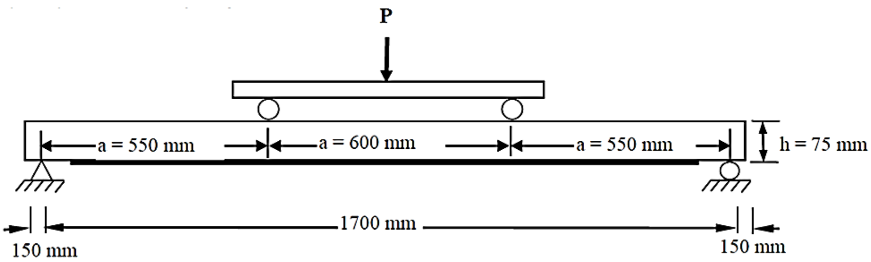


Fig.2: Setup a test by [1].

According to the result of his research, this research created a numerical model to validate the experimental data. A single layer of CFRP slab specimen with a compressive strength of 50 MPa (7.54 ksi) was used in this research. A numerical method was employed to validate the results and conduct a parametric study. This paper summarizes the theories, methodology, and data produced from the FEA utilizing ABAQUS [2] computer software.

III. Numerical Modelling

Concrete Damage Model (CDP)

Reinforced concrete is a complex material to work with. As a result, creating a finite element model that can determine the elastic and plastic behaviour of concrete in tension and compression is necessary. Tensile cracking and compression crushing are two major factors that influence CDP behaviour.

Table no (1): Data defines (C 52 MPA) material

Density (kg/m3)	2570
Young's Modulus: E (MPa)	29,098
Poisson's ratio	0.2
Dilation angle	30
Yield stress in compression (MPa)	27.5

Elastic strain at yield stress	0.0
Compressive ultimate stress (MPa)	52
Inelastic strain	0.000998302
Failure stress in compression (MPa)	11.5
Inelastic Strain at failure	0.004410138
Ultimate tensile stress (MPa)	4.01
Tension stiffening	2×10-6

Elastic-Plastic Model for Steel

When the steel stiffness introduced by the Young's or elastic modulus remains constant at low strain magnitudes, steel reinforcing bars have essentially linear elastic behaviour. It begins to show nonlinear, inelastic behaviour at greater strain magnitudes, which is referred as plasticity. Only the values of Young's modulus (E) and the steel's Poisson's ratio (υ) are required to determine the elastic properties of reinforcement bar material, but the plastic properties of reinforcement steel are defined as a nonlinear stress-strain curve in tabular form. The essential parameters required to define longitudinal bar reinforcement bar models are presented in the next table.

Table no (2): Data defines longitudinal steel material.

Reference density (kg/m^3)	7800
Young's Modulus, E (MPa)	200,000
Tensile Strength, (MPa)	500

Elastic Model for FRP

A linear elastic isotropic material was used to represent the FRP laminate. The stress-strain response of this material was determined to be a linear elastic relationship. In the direction of the fibers, the elastic modulus of FRP composites, $E_{11} = 95GPa$. For the analysis, Poisson's ratio υ_{12} was assumed to be 0.3. When the fiber is modeled as an orthotropic material, the results are not significantly different. As a result, [21] recommends using the simpler isotropy assumption.

Concrete and CFRP Interaction

Two distinct methodologies can be used to assess the interaction between CFRP and concrete. The first considered a tie constraint option for joining two different surfaces together (master concrete surface, slave CFRP surface) so that no relative motion exists between them [22]. A simulation utilizing in this search the cohesive zone model was the second technique. For this simulation, the "hard" contact relationship was used, because it prevents the transfer of tensile stresses across the interface by reducing the expansion of the slave surface into the master surface at the constraint points [2]. Table no (3) summarizes the epoxy resin parameters employed in this numerical analysis.

Table no (3): Mechanical properties of the CFRP-concrete interaction.

Normal stiffness, K_{nn} (MPa/mm)	1834
Shear stiffness, K_{ss} (MPa/mm)	503
Shear stiffness, K_{tt} (MPa/mm)	503
Normal strength, $\sigma_n(MPa)$	4.01
Shear-1 strength, $\tau_t(MPa)$	8.582
Shear-2 strength,$\tau_s(MPa)$	8.582
Normal fracture energy, $G_{nn}(J/m^2)$	90
1st Shear fracture energy, $G_{ss}(J/m^2)$	900
2nd Shear fracture energy, $G_{tt}(J/m^2)$	900
Benzeggagh-Kenane exponent, η	1.45
Stabilization	0.00001

Finite Element Mesh and Analysis

Table no (4) lists the finite element types utilized in the finite element formulation:

Table no (4): Types of finite elements used in numerical simulation.

Part	Type	Description
Concrete Slab	C3D8R	8-node linear brick with hourglass control
Longitudinal Steel	T3D2	2-node, three-dimensional truss element
FRP	S4R	Shell, 4-node, Reduced integration

Following a convergence analysis, a fine mesh with a 25 mm element size was used to the model for better accuracy of the finite element results.

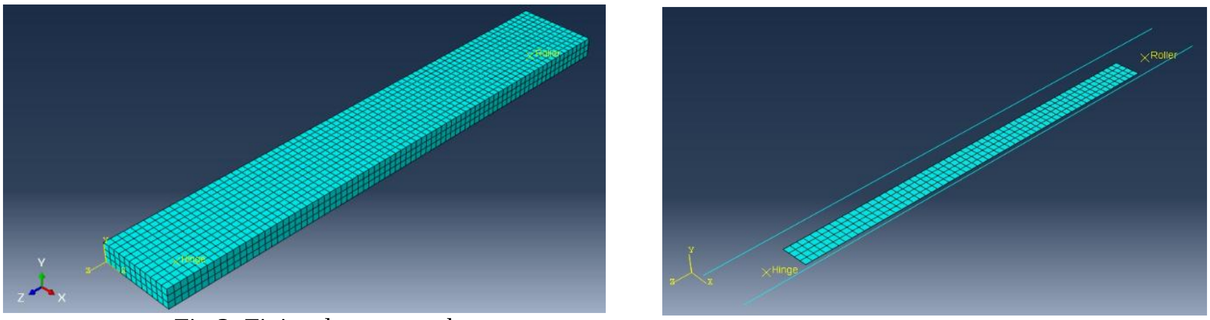


Fig.3: Finite element mesh.

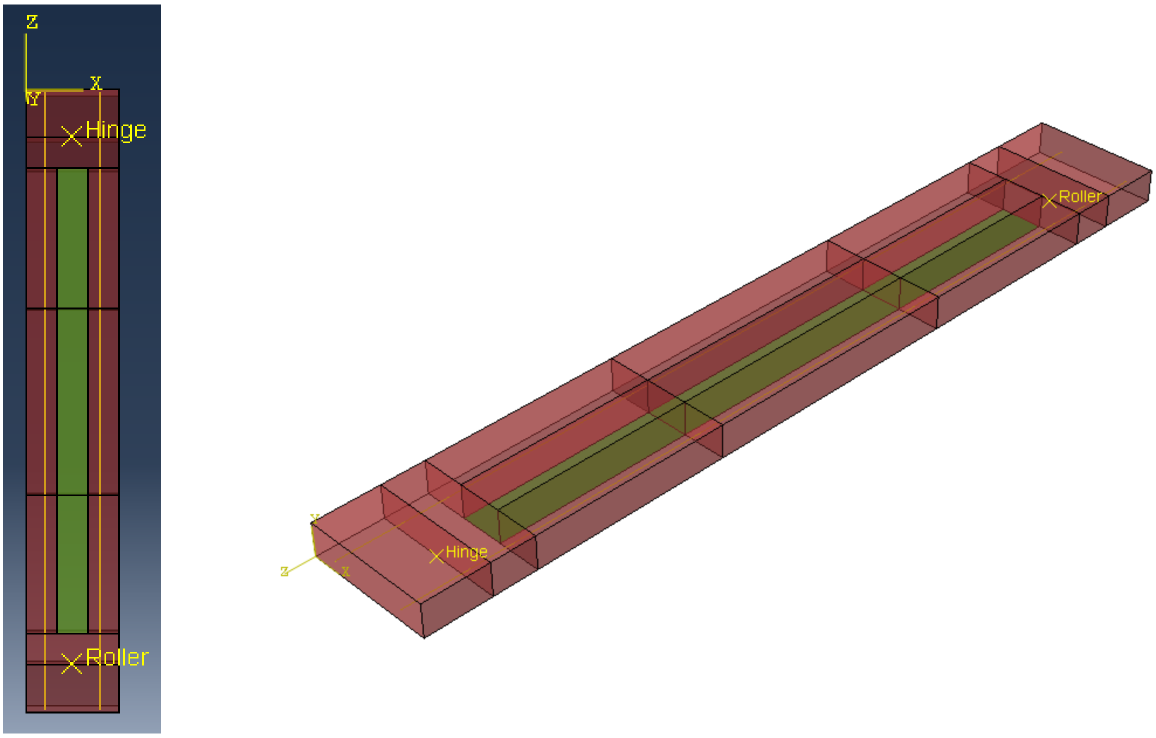
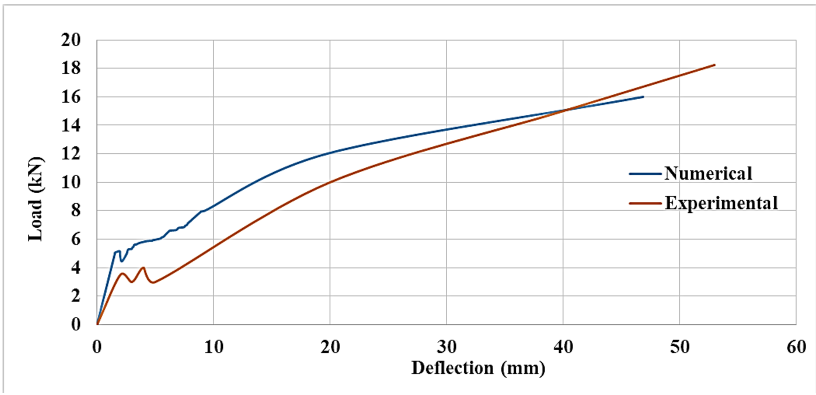


Fig.4: Model geometry.

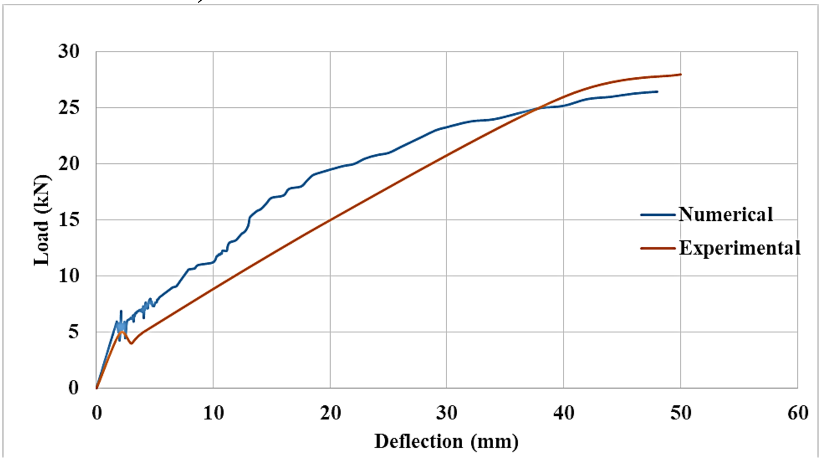
IV. Result Validation and Discussion

Load Deflection Curves

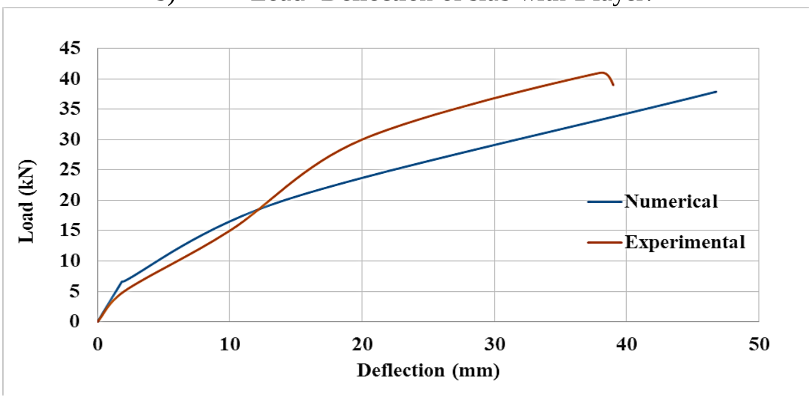
As illustrated in Fig. 5, the slab's load versus deflection curve exhibited good agreement between experimental and numerical results. This showed that the FEM can accurately represent concrete fracture results. The curve of test results was slightly different, possibly because of [1] study did not include the stress versus strain relationship of the concrete in tension and compression.



a) Load- Deflection of control slab.



b) Load- Deflection of slab with 1 layer.



c) Load- Deflection of slab with 2 layers.

Fig.5: Comparisons between experimental and numerical results.

Mode of Failure

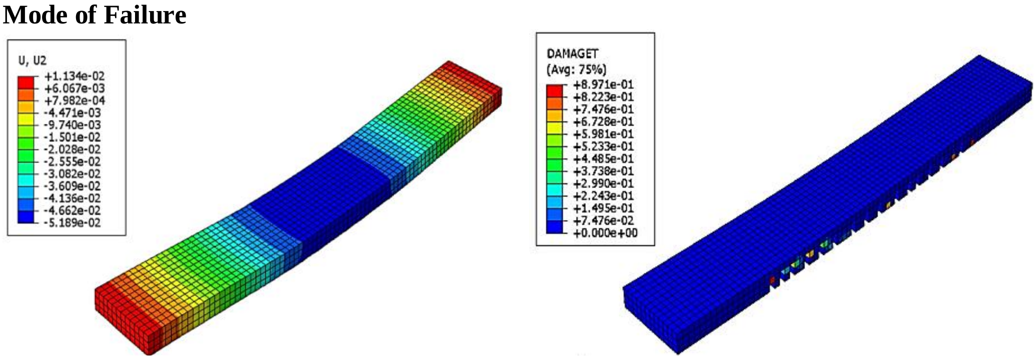
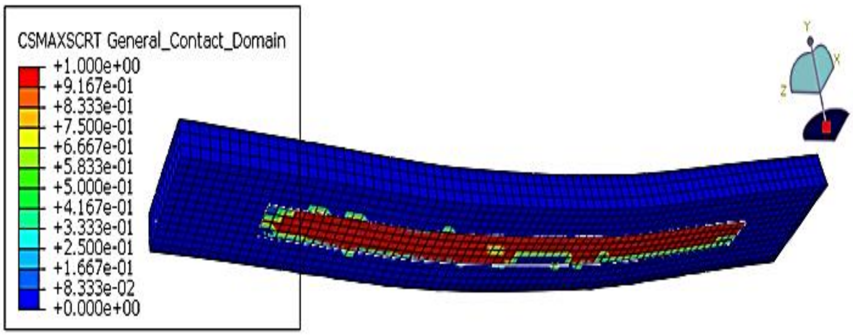
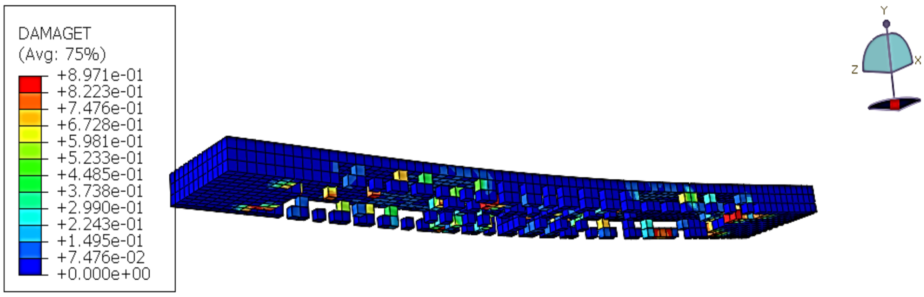


Fig.6: Deflection and Damage at failure of control slab.



a) Damage in Cohesive material for slab with 1layer of FRP.



b) Damage in of slab with 1layer of FRP.

Fig.7: Deflection and Damage at failure of slab with 1layer of FRP.

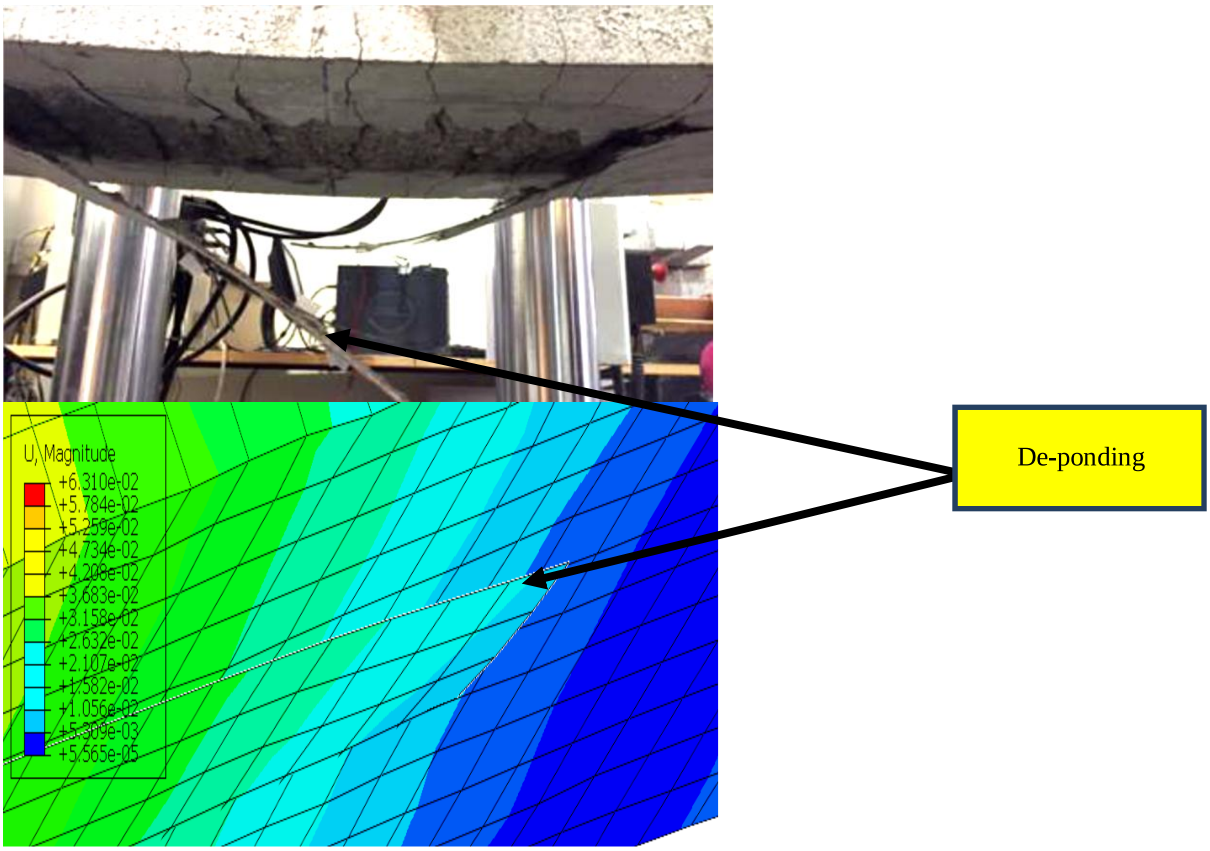


Fig.8: Comparisons between experimental and numerical failure mechanism of slab with 1 layer.

V. Parametric Study

Concrete Strength Effect

In order to study the effect of concrete strength on the capacity of the slab, three concrete compressive strengths of 52 MPa, 40 MPa, and 65 MPa were used to model the slab. In Fig. 9, a load versus displacement curve for various concrete strengths is presented. With lower compressive strength, the slab's load-carrying capacity was found to be reduced conversely when raising the compressive strength.

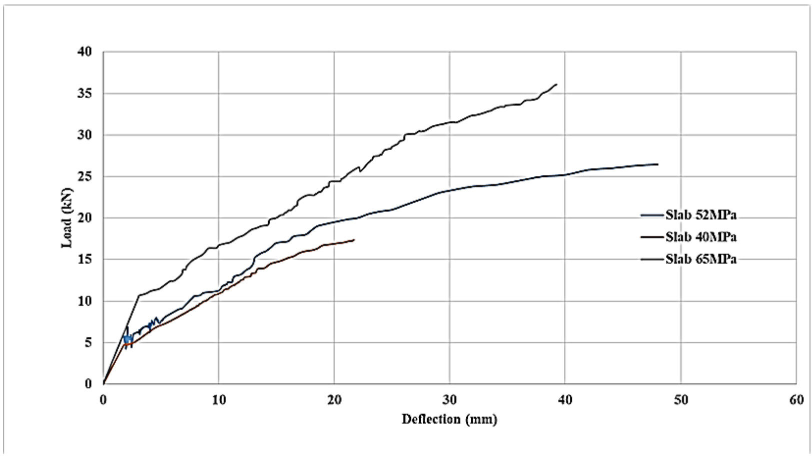


Fig.9: Diagram of load vs. displacement for various compressive strengths.

Longitudinal Steel Effect

In order to study the effect of longitudinal steel ratio on the capacity of the slab, three values of flexural reinforcement ratio (0.67, 1.5, and 2.7%) were used to model the slab. In Fig. 10, a load versus displacement curve for various flexural reinforcement ratios is presented. With a lower flexural reinforcement ratio, the slab's load-carrying capacity was found to be reduced conversely when raising the flexural reinforcement ratio. Noting that when using a high ratio of reinforcement the failure occurs at less value of deflection, which indicates that the collapse in the slab is a sudden collapse.

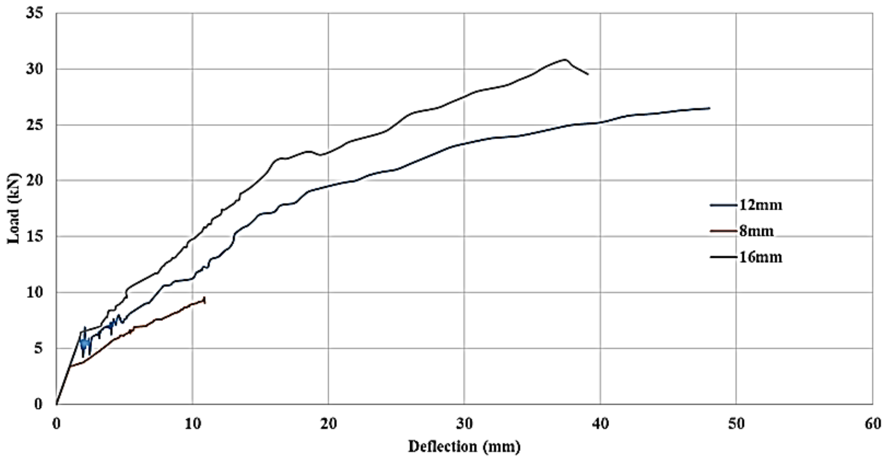


Fig.10: Diagram of load vs. displacement for various flexural reinforcement ratios.

The Effect of using Transverse Layer

As shown in the following figure, there is a slight effect when using a transverse layer of FRP on the capacity of the slab.

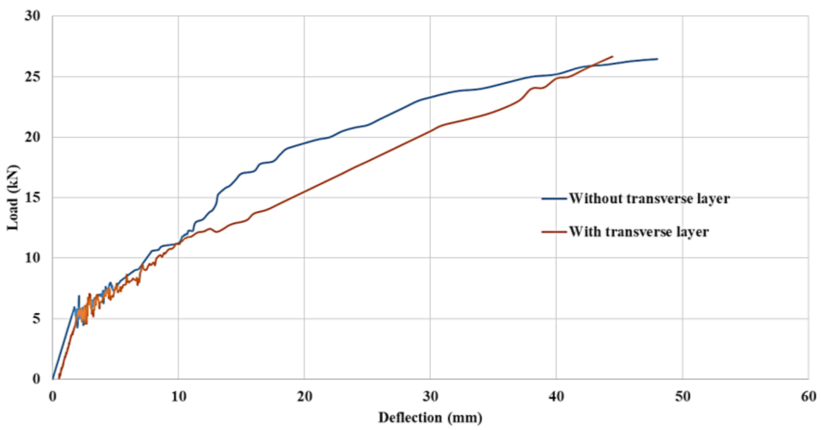


Fig.11: Diagram of load vs. displacement.

VI.Conclusions

Carbon fiber-reinforced polymeric (CFRP) composites have proven to be an effective and cost-effective way of strengthening or repairing reinforced concrete (RC) structures against service loads. This paper examines the effects of strengthening a reinforced thin concrete slab by FRP using a three-dimensional finite element simulation that is reliable. The generated models comprised concrete material nonlinearity, Failure of cohesive material, and debonding from concrete. A detailed parametric analysis was also carried out. Based on the results of this study, the following conclusions were drawn:

1- The experimental model and the provided F.E model have a great agreement in terms of mode of failure.

2- Increasing the concrete strength from 52 MPa to 65 MPa results in a 35 percent increase in slab capacity and a decrease in deflection at failure.

3- When using two layers of FRP, an increase in load capacity was observed by 43%.

4- At using a flexural reinforcement ratio of 2.7% instead of 1.5%, an increase in load capacity was observed by 11%. But when replacing the flexural reinforcement ratio of 0.67 instead of 1.5%, a decrease in load capacity was observed by 66%.

5- There is a slight effect when using a transverse layer of FRP on the capacity of slab.

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