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Finite Element Modeling and Parametric Analysis of High Strength Thin Reinforced Concrete Slabs Strengthened by CFRP Laminates

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ABSTRACT

The flexural performance of thin high-strength concrete slabs externally reinforced with carbon fiber-reinforced polymer (CFRP) laminates at their soffit was studied in this work using a non-linear three-dimensional finite element model. A numerical model was created in this research by using nonlinear finite element software ABAQUS based on the results from an experimental study to validate the experimental results. For the concrete component, a concrete damage plasticity model was applied, and the traction-separation law was used for the CFRP-concrete contact. A thorough parametric study was carried out to comprehend the numerous factors affecting the CFRP reinforced slabs. Concrete's compressive strength, the usage of a transverse laminate of CFRP, various widths of FRP laminates, and the number of layers of CFRP were among the parameters considered in the study. It was found that an improvement in the capacity of the slabs occurred with the increase of compressive strength of concrete and the width of FRP layers. On the other hand, when using a transverse layer there was no effect on the capacity of the slab.

Keywords, strengthening, concrete slab, finite element analysis, ABAQUS, deboning.

1. Introduction

High-rise buildings construction technology enables people to live in close quarters without consuming a the land as the world's population increases. The complexity and applicability of the construction materials industry have increased in recent years. Because of this, a variety of materials have been created and adapted for practically all common uses. Fiber-reinforced polymer (FRP) composite materials are one of the most important technologies to have been produced in the construction materials industry. FRP materials are frequently utilized to repair, strengthen, and restore structures in the form of sheets or bars. Several materials could be used for strengthening, depending on the kind and extent of structural damage. Damage to structures can result from a variety of events, including fires, earthquakes, terrorist attacks, wear and tear, and changes in occupancy. To establish the best methods for repair and strengthening, each type of damage should be analyzed and investigated. A summary of the literature on the flexural and shear behaviour of RC elements reinforced with FRP materials under different schemes provided by Askar, et al. [1] and also examined the effectiveness of various FRP materials and techniques. It also demonstrates a cost comparison of different strengthening methods and the restrictions of FRP reinforcement. The behaviour of the FRP-concrete interface and the effects of different variables on the adhesion behaviour of FRP and concrete surfaces were explored by Godat, et al. [2] by varying the width and thickness of the FRP laminate. One of the most often used techniques to strengthen RC structural elements including slabs, beams, columns, and walls in shear and flexure is externally bonding FRP composite sheets and plates to concrete surfaces Akkaya, et al., Pitcha et al., Vahidpour et al., Askar et al. [3–6]. The effectiveness of FRP strengthening systems over steel alternatives has been demonstrated ACI [7]. FRP systems have also demonstrated a variety of benefits over conventional strengthening techniques, such as the capacity to be simple to install and insulate, having a low maintenance cost, increase structural bonding, having a high strength-to-weight ratio, and using fewer laborers during installation. With the increase in the number of uses for this technology, engineers and academics have conducted several studies to improve it. The performance and capacity of the RC components can be greatly enhanced by bonding these polymers to the outer surface of the reinforced concrete elements according to Anas et al., Nolan et al., Siddikaa et al., Chellapandiana et al., Zhang et al., Jongvivatsakul et al., liu et al., Peng et al., Gotame et al., Jin et al., Abdulrahman et al. [8–18].

However, the author found that there was a gap in the research when it came to discussing the flexible strengthening of thin high-strength slabs with CFRP sheets after analyzing earlier literature and published works. The purpose of this study is to fill that knowledge gap and suggest additional research on the topic.

2. Summary of Experimental Program

The flexural performance of thin RC slabs with external CFRP laminate reinforcement on the tension side and concrete compressive strengths of 72.8 MPa were examined by Mahmoud et al., [19]. 18 slabs were 2.0, 1.7, 0.30, 0.10, and 0.075 m in length, span length, breadth, height, and adequate depth respectively. Depending on their steel reinforcement ratio (ρ), the samples were divided into three groups. There are a total of six samples in each group, three of which are the originals and the other three were examined to guarantee repeatability. The investigated reinforcement ratios were, respectively, 0.45, 1.00, and 1.79 percent. The author referred to these ratios of steel as L (low ratio), M (medium ratio), and H (high ratio). Four samples from each group were additionally strengthened using one or two layers of CFRP laminates (1L and 2L). Additionally, two control un-strengthened specimens served as benchmark specimens in each group. The specimen's details are shown in Figure 1.

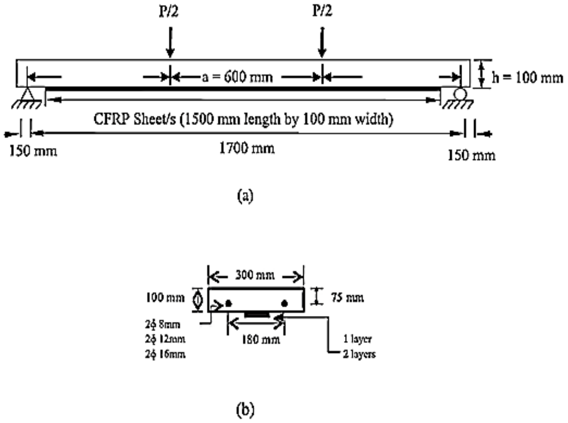


Figure-1: R.C. slab specimens detailing [19]

The test's results were provided in this study and the results were displayed using load versus displacement curves.

This research developed a numerical model to validate the experimental data by the results of the Mahmoud et al. [19] study. In this study single-layer and two layers of CFRP slab specimens with a compressive strength of 72 MPa were used. The results were validated using a numerical approach, and a parametric analysis was conducted. The theories, techniques, and data generated by the FEA using the computer preprogram ABAQUS [20] are summarized in this study.

3. Numerical Modelling

3.1. Concrete Damage Model (CDP)

Working with reinforced concrete is difficult. To determine the elastic and plastic behavior of concrete in tension and compression, a finite element model must be developed. Compression crushing and tensile cracking are two main elements that affect CDP behavior.

Table 1: Data defining the concrete material

Density (kg/m^3)	2550
Young's Modulus: E (MPa)	29,098
Poisson's ratio	0.2
Dilation angle	30
Yield stress in compression (MPa)	32.5
Elastic strain at yield stress	0.0
Compressive ultimate stress (MPa)	72
Inelastic strain	0.000411837
Failure stress in compression (MPa)	19.4
Inelastic Strain at failure	0.00404457
Ultimate tensile stress (MPa)	6.8
Tension stiffening	2×10-6

3.2. Elastic-Plastic Model for Steel

Steel reinforcing bars show nearly linear elastic behaviour when the Young's or elastic modulus-introduced stiffness of the steel remains constant at low strain magnitudes. At higher strain magnitudes, it starts to exhibit plasticity, which is nonlinear, inelastic behaviour. To determine the elastic properties of reinforcement bar material, only the values of Young's modulus (E) and the steel's Poisson's ratio (υ) are needed. However, a nonlinear stress-strain curve in tabular form is used to define the plastic characteristics of reinforcement steel.

Table 2 lists the critical variables needed to define longitudinal bar reinforcement.

Table 2: Data defining steel material

Reference density (kg/m^3)	7800
Young's Modulus, E (MPa)	200,000
Yield stress (MPa)	550
Tensile Strength, (MPa)	667

3.3. Elastic Model for FRP

For the FRP laminate, a linear elastic isotropic material was utilized. This material's stress-strain curve was applied to have a linear elastic relationship. The elastic modulus of FRP composites is E_11=95GPa in the direction of the fibers. The tensile strength of FRP is 1240 MPa and the Poisson's ratioυ_12 was set to be 0.3 for the analysis. The thickness of the FRP layer is 1.02×10-3 m. The results are not materially different when the fiber is modeled as an orthotropic material. As a result, Obaidat, M. [21] Suggests making use of the less complicated isotropy assumption as an orthotropic material. As a result, Obaidat, M. [21] suggests making use of the less complicated isotropy assumption.

3.4. Concrete and CFRP Interaction

To evaluate how CFRP and concrete interact, two different techniques might be employed. The first considered the tie constraint option for combining two dissimilar surfaces (master concrete surface, slave CFRP surface) so that there is no relative motion between them according to Moldovan et al. study [22]. The second method was a simulation using the cohesive zone model for this search. The "hard" contact relationship was chosen for this simulation because it reduces the expansion of the slave surface into the master surface at the constraint points, preventing the transfer of tensile stresses across the interface [22]. The epoxy resin parameters used in this numerical analysis are listed in Table 3.

Table 3: Mechanical properties of the CFRP-concrete interaction.

Normal stiffness, K_{nn} (MPa/m)	1834×10^3
Shear stiffness, K_{ss} (MPa/m)	503×10^3
Shear stiffness, K_{tt} (MPa/m)	503×10^3
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

3.5. Finite Element Mesh and Analysis

The finite element types used in the finite element formulation are listed in Table 4. The slab was modeled as simply supported with proper boundary conditions. Eight-node linear brick elements with reduced integration (C3D8R) were used for the concrete. The reinforcement was modeled using two-node truss elements (T2D3E). Four-node doubly-curved thin shell elements with reduced integration (S4R) were used to represent CFRP laminates. A fine mesh with a 0.025 m element size was applied to the model after a convergence study for increased accuracy of the finite element results.

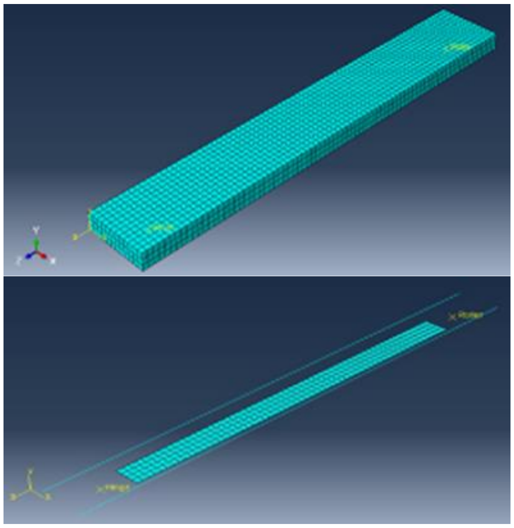


Figure2: Finite element mesh

Table 4: Types of finite elements used in numerical simulation.

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

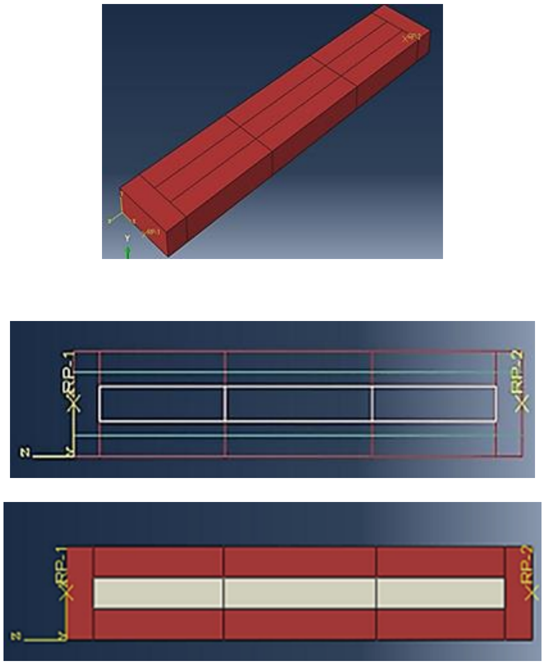
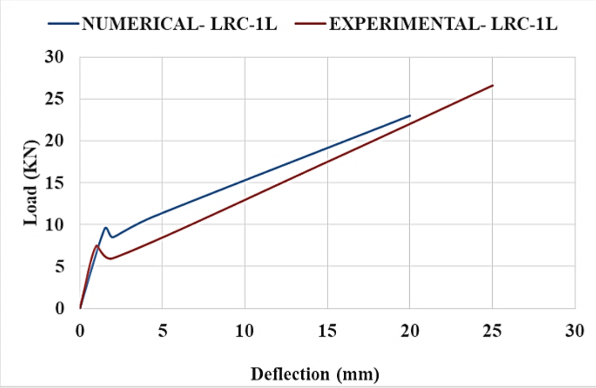


Figure3: Model geometry

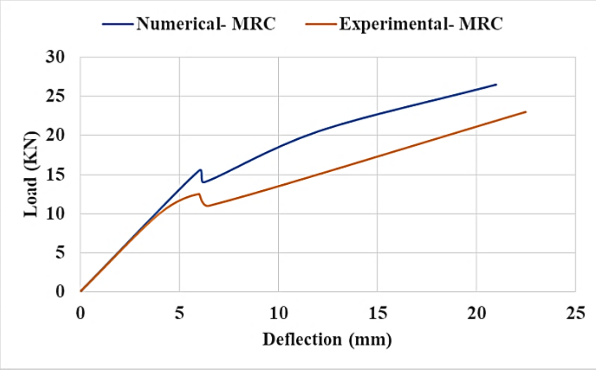
4. Validation and Discussion

4.1. Load Deflection Curves

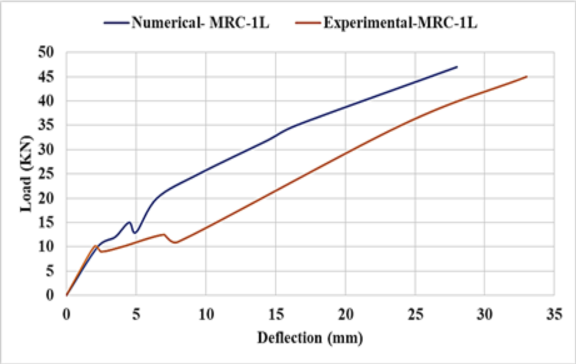
The load versus deflection curve and failure mode for the slab showed good agreement between experimental and numerical results, as shown in Figure 4 and Figure 5. This demonstrated that the FEM can accurately describe the outcomes of concrete fracture. The fact that [19] study did not take into account the stress versus strain relationship of the concrete in tension and compression may be the reason why the curve of test results was slightly different.



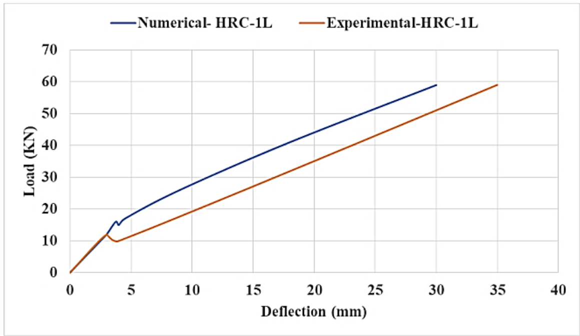
a) Load- Deflection of Low Reinforcement slab with 1 layer.



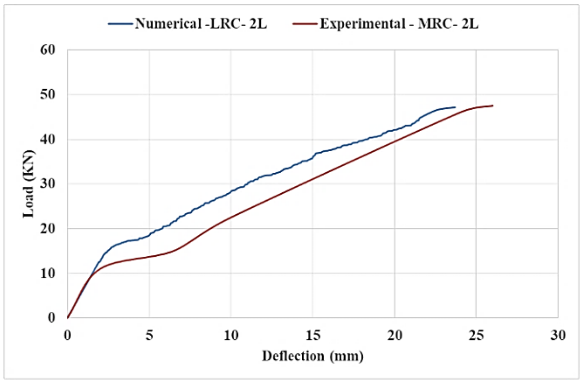
b) Load- Deflection of Medium reinforcement - control slab.



c) Load- Deflection of medium reinforcement with 1 layer



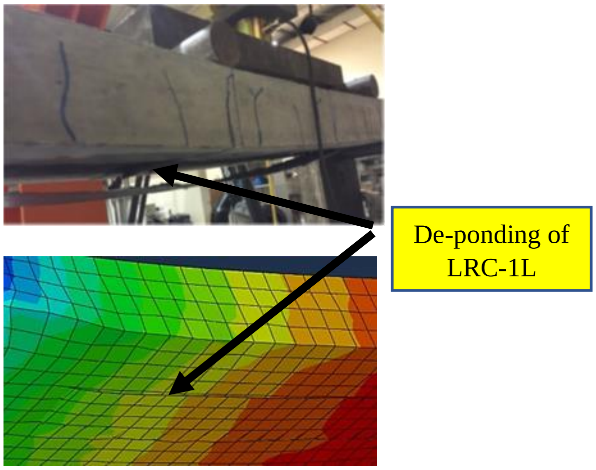
d) Load –Deflection high reinforcement ratio with one layer



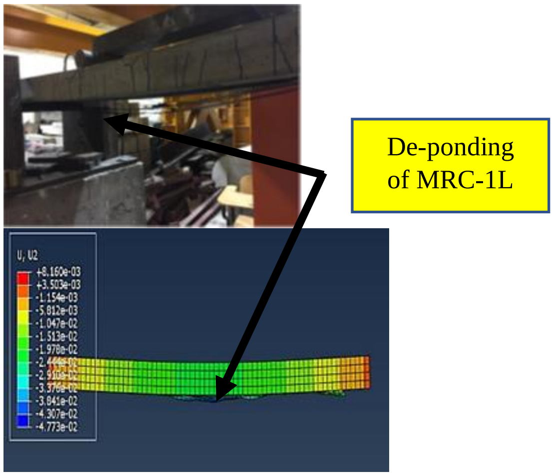
e) Load-deflection of medium reinforcement ratio with 2 Layer

Figure 4: Comparisons between experimental and numerical results.

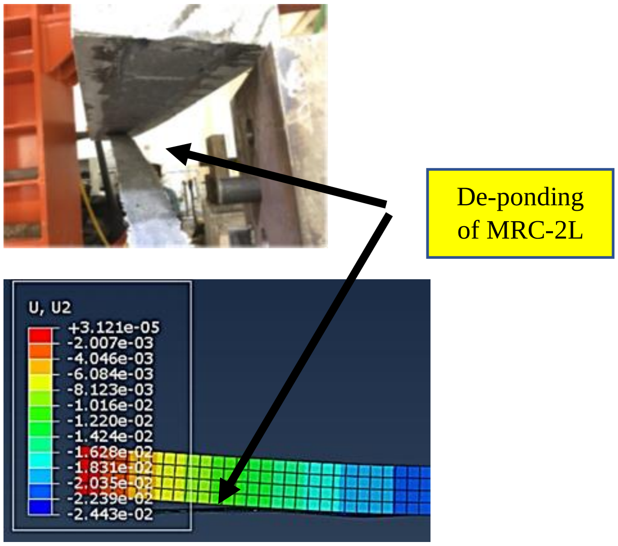
4.2. Mode of Failure



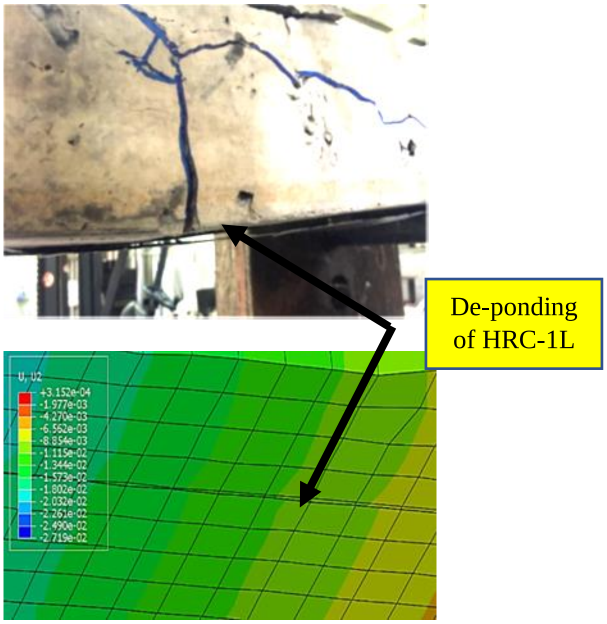
a) Numerical and Experimental failure mode of low reinforcement ratio with 1 Layer



b) Numerical and Experimental failure mode Of medium reinforcement ratio with 1 Layer



c) Numerical and Experimental failure mode of medium reinforcement ratio with 2 Layer



d) Numerical and Experimental failure mode of high reinforcement ratio with 1 Layer.

Figure 5: Comparisons between experimental and numerical failure mechanism of the slab.

5.Parametric Study

This study aims to understand the various factors affecting the CFRP strengthened slab. The parameters used for the study include compressive strength of concrete, the width of FRP layers, and using transverse layer of FRP. The validated FEA model from the numerical analysis was used in the parametric analysis.

5.1. Concrete Strength Effect

Three concrete compressive strengths of 72 MPa, 60 MPa, and 80 MPa were utilized with a medium steel ratio to model the slab to examine the impact of concrete strength on its capacity. A load versus displacement curve for different concrete strengths is shown in Figure 6. It was discovered that the slab's load-carrying capability decreased with lower compressive strength and increased with higher compressive strength. As shown in Figure 7 the damage at failure is tension damage and de ponding of layer of FRP that occurs in all modes of failure.

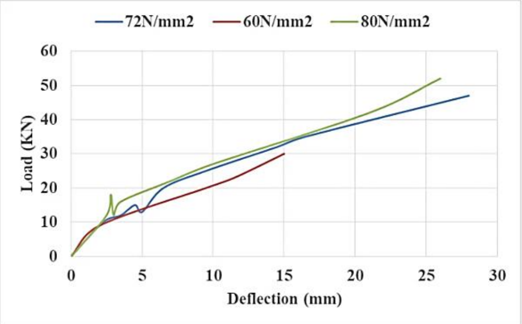
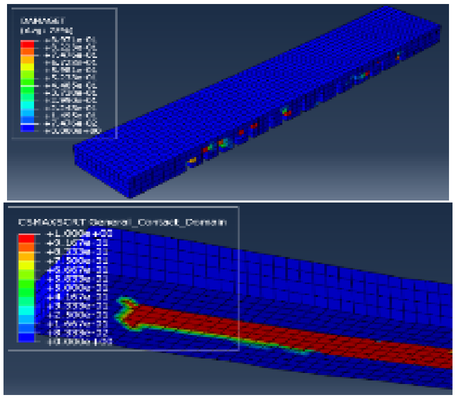
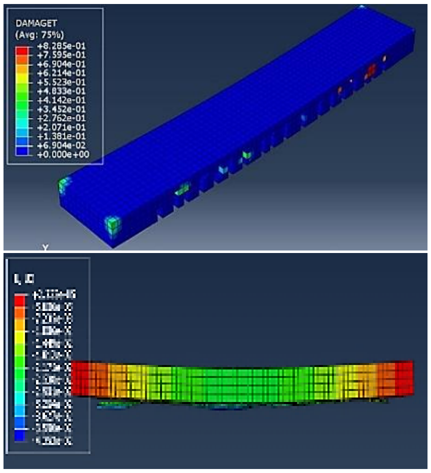


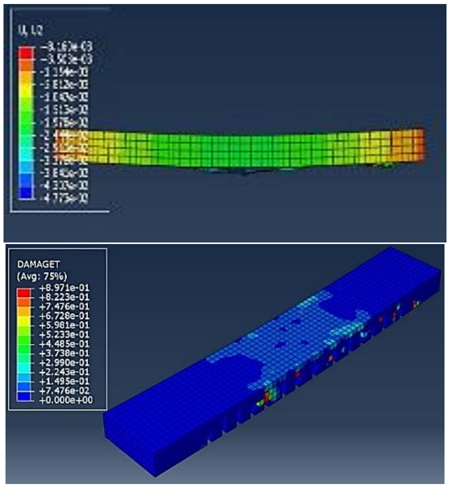
Figure 6: Diagram of load vs. displacement for various compressive strengths



a) Damage and De-bonding of medium reinforcement concrete slab with 1 Layer (60MPa)



b)Damage and De-bonding of medium reinforcement concrete slab with 1 Layer (80MPa).



c) Damage and De-bonding of medium reinforcement concrete slab with 1 Layer (72MPa).

Figure7: Damage and De-bonding of various compressive strengths.

5.2. Width of FRP Effect

To study the effect of the width of the FRP layer on the capacity of the slab, two values of width (50mm and 150mm) were used to model the slab. In Figure 8, a load versus displacement curve for various widths is presented. With a lower value of the width, the slab's load-carrying capacity was found to be reduced conversely when raising the width of the FRP layer. As shown in Figure 9 the damage at failure is tension damage and de ponding of layer of FRP that occurs in all modes of failure

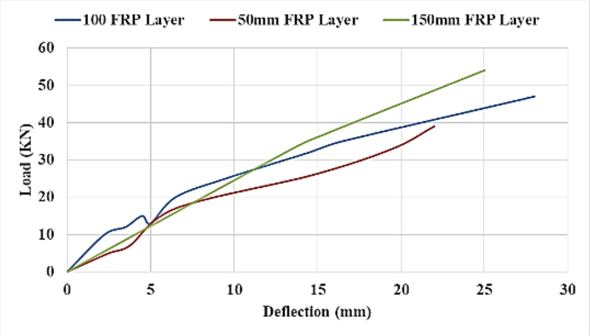
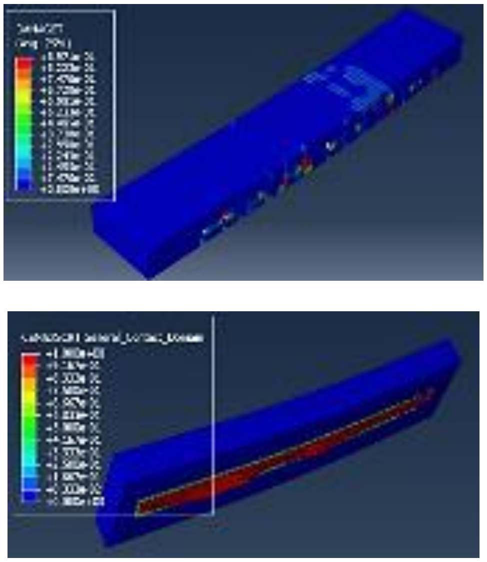
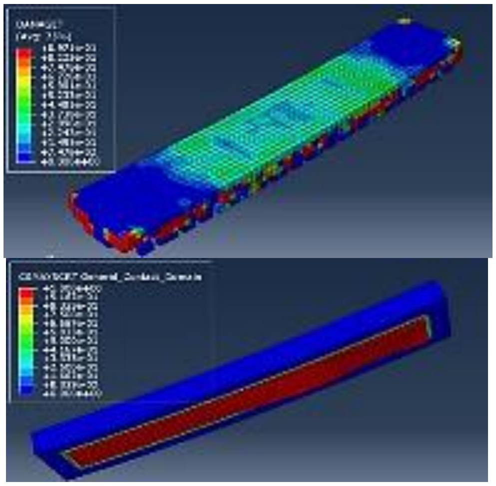


Figure 8: Diagram of load vs. displacement for various widths of FRP layer.



a) Damage and De-bonding of medium reinforcement concrete slab with 1 Layer (50mmFRP Layer).



b) Damage and De-bonding of medium reinforcement concrete slab with 1 Layer (150mmFRP Layer).

Figure 9: Damage and De-bonding of various FRP layer widths.

5.3. The Effect of using Transverse Layer

The capacity of the slab is slightly impacted when a transverse layer of FRP is used, as is depicted in the following picture. As shown in Figure 11 the damage at failure is tension damage and de ponding of layer of FRP that occurs in all modes of failure.

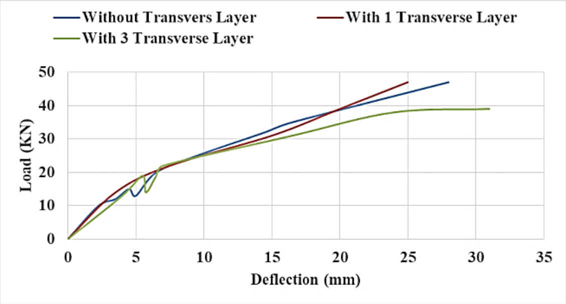
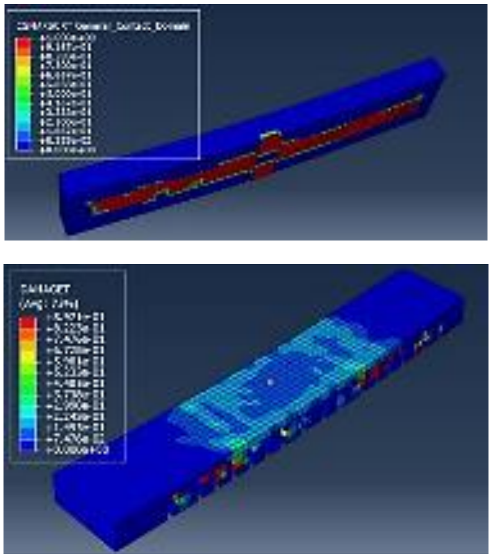
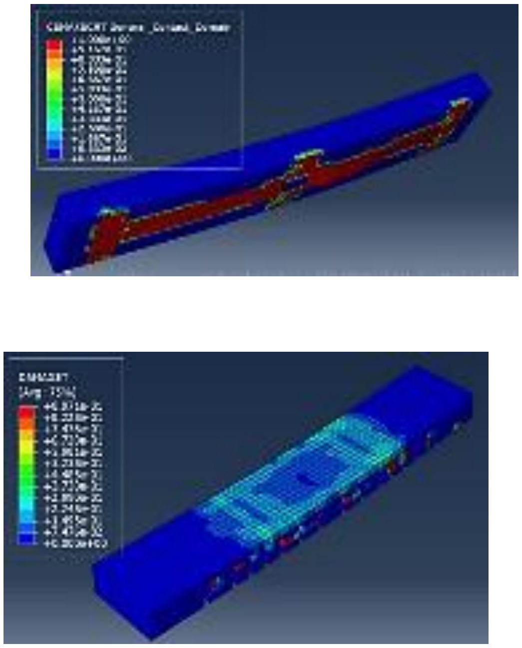


Figure 10: Diagram of load vs. displacement



a)Damage and De-bonding of medium reinforcement concrete slab with one transverse FRP layer



b) Damage and De-bonding of medium reinforcement concrete slab with 1 Layer (Three Transverse FRP layers).

Figure 11: Damage and De-bonding for transverse FRP layers.

6.Conclusions

Reinforced concrete (RC) structures can be strengthened or repaired cost-effectively by using carbon fiber-reinforced polymeric (CFRP) composites. This study uses a trustworthy three-dimensional finite element simulation to explore the impacts of reinforcing a reinforced thin concrete slab using FRP. The generated models comprised concrete material nonlinearity, Failure of cohesive material, and debonding from concrete. Additionally, a comprehensive parametric analysis was performed. The following conclusions were reached based on the study's results:

1- In terms of the mode of failure, the experimental model and the given F.E model agree very well.
2- Increasing the concrete strength from 72 MPa to 80 MPa results in an 11.34 percent increase in slab capacity and a decrease in deflection at failure.
3- At using 150mm width of FRP layer instead of 100mm, an increase in load capacity was observed by 16.64%. But when replacing the width 50mm instead of 100mm, a decrease in load capacity was observed by 16.2%.
4- There is a slight effect when using one transverse layer of FRP in the middle of the span of the slab but when using three transverse layers at the end of the slab, an increase in the capacity of the slab by 9.04%

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