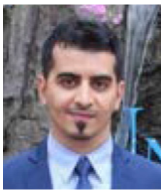
SIMULATING THE FLEXURAL PERFORMANCE OF ONE-WAY REINFORCED CONCRETE SLABS WITH OPENINGS STRENGTHENED BY THE USE OF CARBON FIBER REINFORCED POLYMER (CFRP)



Dedicated to Prof. György L. Balázs
for his 65th birthday

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Over the past decade, the use of fiber-reinforced polymers (FRPs) as bonding agents to enhance and rehabilitate concrete structures has become widespread. Despite the demonstrated effectiveness of this approach in numerous experimental studies, there are still concerns about the time and expense required for these investigations. To address this issue, The objective of this study was to investigate how the carbon fiber-reinforced polymer (CFRP) reinforcement affects the bending performance of one-way reinforced concrete slabs using advanced finite element software (ABAQUS). To investigate the impact of various factors on slab performance, two models of one-way RC slabs were developed, taking into account concrete grade, number of CFRP layers, and opening size (600x600mm). By comparing the results obtained in this study with existing experimental data, the findings indicated that the approach adopted in this research could offer a cost-effective and efficient way to evaluate the performance of FRP-strengthened concrete structures.

Keywords: Carbon fiber reinforced polymer (CFRP); Strengthening; Finite element analysis (FEA); one-way RC slab

1. INTRODUCTION

FRP's (Fiber Reinforced Polymers) have been widely employed in recent times for the purpose of strengthening or reinforcing structural components, whether by externally wrapping them with sheets or using them as internal reinforcement. Additionally, the methods that use externally bonded FRP materials are the most commonly used techniques for upgrading and reinforcing existing structures that have been damaged (Al-Amery and Al-Mahaidi 2006). This is because they possess a high ratio of strength to weight, are highly rigid, can be easily installed, and maintain a stable shape throughout their operational lifespan (Costa and Barros 2010), (Rafi et al. 2008), (Benjeddou et al. 2007).

Many studies (Kim and Shin 2011), (Toutanji et al. 2006), (Anania et al. 2005), (Li et al. 2008), (Gao et al. 2005), (Ceroni 2010), (Rafi et al. 2008), (Benjeddou et al. 2007) have been conducted on reinforced concrete (RC) beams that were reinforced using FRP sheets in order to enhance their flexural strength. This was achieved through experimental, finite element, and analytical methods. The findings of these studies indicate that the use of FRP to reinforce beams in flexural strengthening can prevent debonding failure if a properly designed anchorage is implemented (Kim and Shin 2011), (Rafi et al. 2008), (Ceroni 2010), (Esfahani et al. 2007), (Chajes et al. 1994), (Wenwei and Guo 2006). This provides a favorable level of both strength and ductility when subjected to flexural stress. Concrete slabs, on the other hand, are a common building element used in various construction projects, ranging from residential buildings to commercial facilities. These slabs can sometimes have openings or penetrations, such as for ducts, pipes, or other services.

However, these openings can weaken the overall structural integrity of the slab and compromise its load-carrying and energy dissipation capabilities, stiffness, and ductility of the slabs (Anil et al. 2013). To ensure the strength and stability of the slab with openings, various repair and strengthening techniques are employed. One effective method for strengthening concrete slabs with openings is the use of Carbon Fiber Reinforced Polymer (CFRP) sheets. CFRP sheets are made of high-strength carbon fibers embedded in a polymer matrix, which provides exceptional tensile strength, stiffness, and durability. The use of CFRP sheets for concrete slab strengthening has gained significant attention in recent years due to their high strength-to-weight ratio, ease of installation, and durability. By applying CFRP sheets to concrete slabs with openings, their load-carrying capacity and overall performance can be significantly improved, ensuring the structural integrity of the slab and extending its lifespan. Despite the many benefits of using CFRP to strengthen one-way RC slabs, most research in this area is based on experimental studies and numerical modeling has been limited. Civil engineering departments at universities could greatly benefit from further research into the use of CFRP, exploring its advantages and disadvantages and the impact on the flexure and shear capacity of structural members. Additionally, further research could lead to reduced cost, time, and work required for experimental studies.

One of the first studies that focused on concrete slab strengthening was Ebead and Marzouk (2004), which investigated nine square slabs with dimensions of 1.90 m and thickness of 0.15 m. The slabs had different amounts of reinforcement and were simply supported along the edges with free corners. They were loaded through the column stub at the center. The authors found that failure mode depended on the reinforcement ratio, with slabs having less than or equal to 0.5% reinforcement failing in flexure and those with 1.0% or more failing due to punching shear. The lowest first crack loads were observed for slabs with a reinforcement ratio of 0.35%, while the use of CFRP and GFRP slightly increased the equivalent reinforcement ratio. As the reinforcement ratio increased, deflection values decreased, with a decrease from 42 to 24 mm for ratios of 0.35% to 1.0%. The load-deflection curve for flexural strengthening specimens had a higher slope than that of the reference specimens, and their average deflection at ultimate load was approximately 0.6 that of the reference specimens. Flexural strengthening specimens also experienced less deformation due to the effect of the FRP materials on the overall behavior of the slabs in relation to punching-shear strengthening. Furthermore, a study was conducted by Smith and Kim (2009), which comprehensively explored the use of (FRP) composites in strengthening one-way reinforced concrete slabs with central holes. The study involved testing four wide slabs with cut-outs and two narrow slabs without cut-outs to evaluate the impact of different load application positions on the performance of the slab. The results of the study were impressive, with all of the FRP-strengthened slabs exhibiting a higher load-carrying capacity compared to their unstrengthened counterparts. However, the failure mode in all cases was debonding at intermediate cracks, which were found to be diagonal and originating from the corners of the cut-outs of the slabs. This study did not only assess the load-carrying capacity of the FRP-strengthened slabs but also examined how this strengthening method could distribute stresses around the holes in RC structures, the failure mechanisms, and the pre and post-debonding behavior of the strengthened structures. To achieve this, the researchers recorded strains on the FRP, concrete, and internal steel reinforcement, as well as deflections at different positions on the slab surfaces. Overall, this study provided valuable insights into the effectiveness of FRP composites in strengthening concrete slabs with central holes and highlighted the importance of considering failure modes in the design process. in addition to their experimental work a finite element model was created to predict the ultimate moment of resistance around crucial crack lines, and it was discovered that the model's predictions closely aligned with the experimental outcomes. The model successfully accounted for the varied bending behaviors of the slabs and the debonding failure of the reinforced slabs, indicating its suitability for application in future strengthening initiatives.

Last but not least Anil et al. (2013) conducted research on the flexural Performance of one-way RC slabs that were strengthened using CFRP strips. The study focused on the impact of the size and location of openings in the slab on its behaviour. Three square openings with side lengths of 300 mm, 400 mm, and 500 mm were examined and placed in either the bending or shear zone. 13 slabs were examined, with one serving as a reference, six without CFRP strengthening, and six with CFRP reinforcement around the opening. The study found that the use of CFRP strips greatly increased the load-carrying capacity and stiffness of the specimens, and the technique could be quickly and cost-effectively applied during construction or while the structure was in use, without disturbing occupants. Nevertheless, there has been no numerical analysis conducted on this research in order to investigate additional parameters, while minimizing the need for expensive and time-consuming experimental work.

2. METHODOLOGY

Structural engineering often utilizes finite element analysis to gather valuable information on structure stress and strain distribution. This information is not readily available through experimental means, and numerical investigation can provide complementary data for better understanding. Additionally, finite element models can be subjected to parametric studies to optimize a structural design. Advances in FE formulation have resulted in sophisticated algorithms capable of handling complex geometries, contact interactions, plasticity, and large deformations (Starossek et al. 2010). In this chapter, three-dimensional finite element simulations with nonlinear characteristics were produced employing the commercially available ABAQUS/Standard 6.13 program.

In this study, two models of one-way reinforced concrete slabs were analyzed. The first model, referred to as Slab1, was a control slab with a 500×500 mm opening located at the region with maximum moment. The second model, Slab2, was identical to the first but was strengthened by adding CFRP strips. Both slabs were simply supported with dimensions of 3000×1000×150 mm in length, width, and depth respectively.

Anil et al. (2013) conducted an experiment aimed at investigating the flexural behavior of one-way reinforced concrete slabs that contained structural holes, and to assess the impact of (CFRP) strengthening on this behavior. The experimental setup involved the use of eleven steel rebars of Ø10 for main reinforcement, and transverse reinforcement was provided with Ø10 steel rebars that were spaced at 250 mm. To simulate a real-world scenario, the reinforcement around the opening was removed. The slab specimens underwent a four-point loading examination where the ratio between the shear span and the effective depth was 7. The load on the separator beam›s center was evenly divided and applied as two concentrated loads, allowing for the assessment of the slab›s flexural strength and behavior under load. The experimental results were analyzed to evaluate the effectiveness of the CFRP stips strengthening in improving the flexural behavior of the slabs, and to identify any potential issues that may arise when using such reinforcement in practice. *Figs. 1 and 2* show the arrangement of loading, reinforcement specifications, and dimensions of the specimens.

CFRP strengthening scheme of specimen Slab2 is shown in *Fig. 3.*

Fig. 1: Load configuration for all slab samples (all dimensions are in mm)

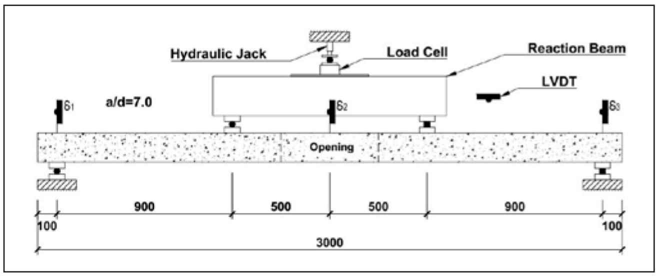
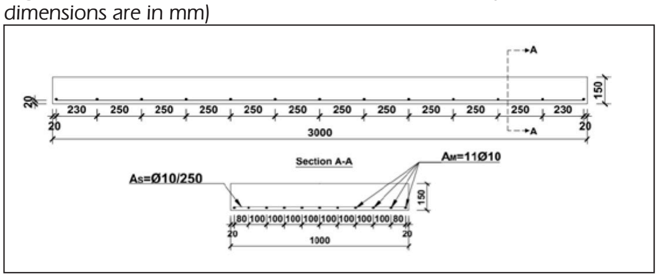


Fig. 2: Reinforcement details and dimensions of the specimen (all dimensions are in mm)



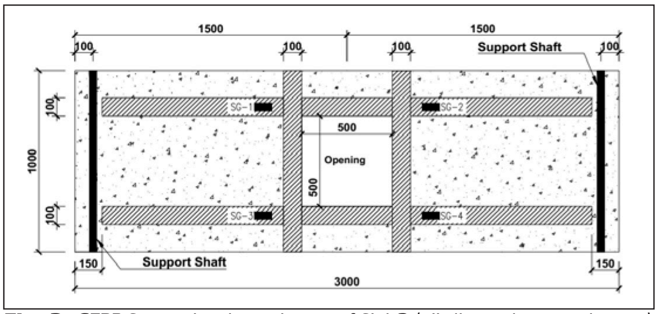


Fig. 3: CFRP Strengthening scheme of Slab2 (all dimensions are in mm)

2.1 Finite Element Analysis

Because of the simplicity of the examined specimen, it was possible to model it as a full-scale slab without being segmented for its symmetry. However, some measurements of the loading rods, support rods, loading plate, and reaction beam were missing from the experimental details. To overcome this challenge, these unknown measurements were estimated systematically to produce results that were as close as possible to the experimental results. The estimated dimensions can be seen in *Fig. 4*. Concrete, loading rods, support rods, loading plate, and reaction beam were modeled using the three-dimensional eight-node element (C3D8), reinforcement was modeled using the three-dimensional two-node truss element (T3D2), and the CFRP strips were modeled using a 4-node shell element (S4R).

A convergence study was conducted on the full-scale slab model to determine the optimal mesh density. This is accomplished by decreasing the mesh size and observing the resulting changes in the ultimate load. The RC slab was modeled with mesh sizes 120, 100, 60, 40, and 30 mm, *Fig. 5* shows that the difference in the ultimate load was negligible when the mesh size was reduced from 40 mm to 30 mm. As a result, the 40 mm model was selected for all slabs, as depicted in *Fig. 6*.

Fig. 4: Estimated dimensions in mm

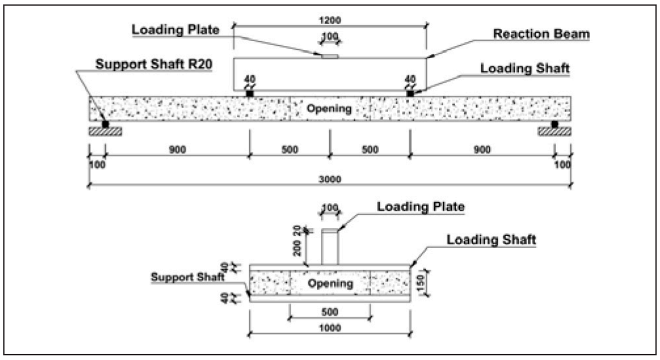
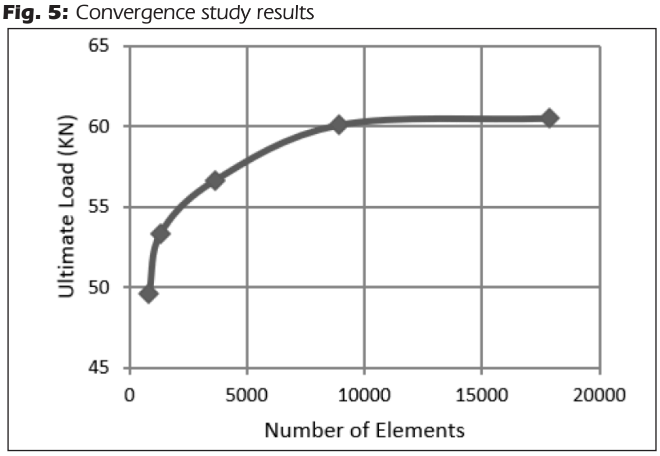


Fig. 5: Convergence study results



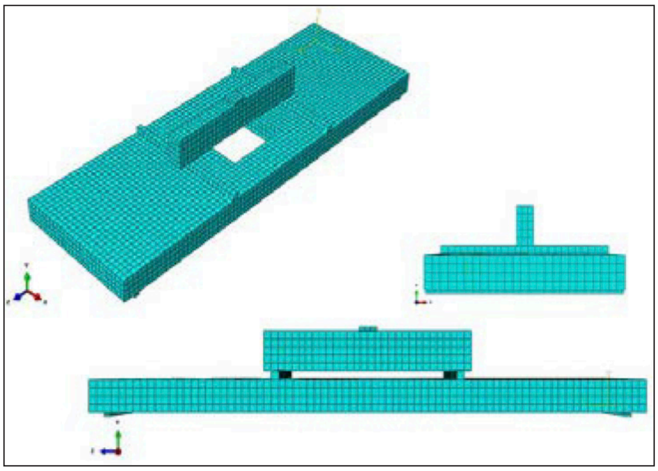


Fig. 6: Finite element mesh

2.2. Loading and boundary conditions

In the numerical analysis, a uniform load was applied to the loading plate, which transferred the load to the reaction beam. The reaction beam then divided the load into two equal parts that acted on the loading shafts. The load was ultimately transferred to the top surface of the simply supported slab. To model the interaction between the loading plate, reaction beam, loading shafts, and concrete, a surface-to-surface contact was used.

It is important to note that the bond between the CFRP strips and the concrete slab was perfect, and the adhesive layer was not considered in the numerical analysis . This was because the primary failure mechanism observed in the strengthened slabs, as detailed in the investigations by Anil et al. (2013), was the failure of the CFRP material itself (as depicted in *Fig. 7*); so, there is no need to model the bonding material between CFRP and RC slab surfaces. To accurately simulate the system, the supporting rods were fixed at their lower surface, preventing any movement in any direction, while the upper surface of the loading plate was fixed in all directions except for vertical displacement. The lateral faces along the length of the slab were restricted horizontally from movement in the X-direction and from rotating in the Y and Z-directions.

2.3 Characteristics of Materials and Assumed Parameters

In this paper, two specimens from the experimental test with the same opening size have been used: the first is without CFRP strengthening and compared with FEM model Slab1, and the second is with CFRP strengthening and compared with FEM model Slab2. The material properties used in the analysis of the slabs are listed in *Tables 1 and 2*, which detail the properties of the concrete, reinforcement, and CFRP fabric. However, certain properties, like steel's Young's Modulus, had to be estimated and were assumed to fall within the range of 200 to 210 GPa, as their exact values were deemed to have an insignificant impact on the result of the study.

3. ANALYSIS RESULTS

Finite element analysis is a powerful tool in the field of structural engineering that can provide valuable insights into the stress and strain distributions within structures. Unlike experimentation, numerical simulations can capture a range of detailed information, which can serve as complementary data to enhance understanding. Moreover, the use of finite element models allows for the exploration of a variety of model parameters through parametric studies, thus improving the design process. In this chapter, we employ ABAQUS, a commercially available simulation software, to develop 3D, materially nonlinear finite element models. These models are designed to accurately capture the sophisticated behaviors of the structures under study and provide an effective means of predicting their performance.

Table 1: Concrete characteristics

Slab1		
Modulus of elasticity (MPa)*	E_c	19661
Compressive strength (MPa)	f'_c	17.5
Tensile strength (MPa)**	f_t	1.38
Poisson's ratio***	v_c	0.2
Slab2		
Modulus of elasticity (MPa)*	E_c	21071
Compressive strength (MPa)	f'_c	20.1
Tensile strength (MPa)**	f_t	1.48
Poisson's ratio***	v_c	0.2

* $E_c = 4700\sqrt{f'_c}$ ** $f_t = 0.33\sqrt{f'_c}$ *** Assumed value

Table 2: Main, transverse reinforcement bars and CFRP fabric characteristics

Main and distribution reinforcement bars		
Modulus of elasticity (GPa)*	E_s	200
Steel yield strength (MPa)	f_y	480
Ultimate tensile strength (MPa)	f_{pu}	627
Poisson's ratio*	v_s	0.3
Bar cross-sectional area (mm^2)	A_s	78.5
CFRP sheet		
Thickness (mm)	t	0.12
Poisson's ratio*	v_f	0.3
Young's modulus (GPa)	E_f	231
Tensile strength (MPa)	f_y	4100

* Assumed value

3.1 Analysis results of RC Slab1

Fig. 8 compares the load-deflection curves obtained from the experimental test and the finite element analysis for RC Slab1. The results from the numerical simulation are in close alignment with the experimental findings throughout the entire loading process. However, a slightly stronger numerical response can be observed near the maximum load. The predicted maximum load of 61.6 kN is slightly higher than the experimental value of 60 kN, with a difference of 2.66%. The calculated maximum deflection of 98.9 mm is also slightly higher than the experimental value of 98.7 mm, with a difference of 0.19%. *Fig. 9* shows the distribution of the plastic strain of Slab1 at the maximum load. The figure suggests that the areas with the highest plastic strain are the zones most impacted by the loading and that cracks are likely to form in these areas.

Fig. 7: Example pictures for CFRP failures

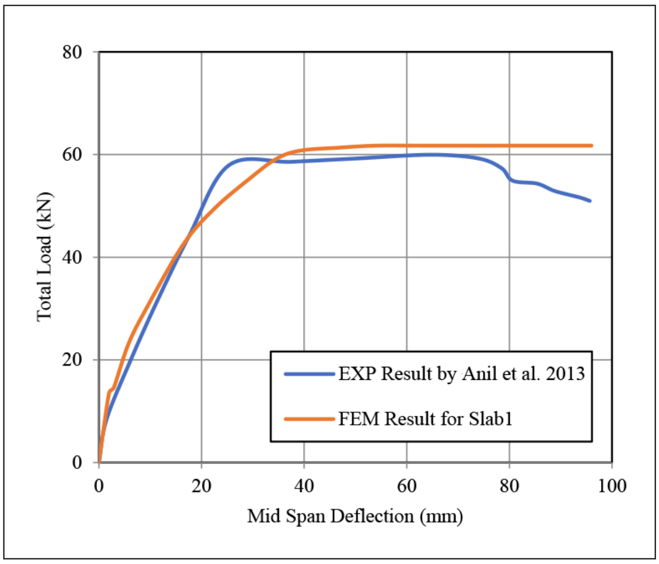


Fig. 8: Exp. and num. load-displacement curve of Slab1 without CFRP strengthening

3.2 Analysis results of RC Slab2

The load-deflection behavior of RC slab2 reinforced with CFRP strips is depicted in *Fig. 10*. The experimental and analytical results show good agreement throughout the loading range, with a slightly stiffer response observed in the experimental data at stages close to ultimate load. The experimental ultimate load was found to be 93.8 kN, while the numerical result was 88.7 kN, resulting in a difference of 5.58% between predicted and actual values. Additionally, the experimental ultimate deflection of 93.2 mm was marginally higher than the numerical result of 92.9 mm, with a difference percentage of 0.32%. *Fig. 11* presents the magnitude of the plastic strain of Slab2 at the ultimate load, indicating that areas with the highest plastic strain are susceptible to cracking and are the most influenced zones.

4. PARAMETRIC STUDY

The objective of this study is to investigate the effect of various parameters on the flexural behavior of reinforced concrete (RC) slabs that are reinforced with (CFRP) strips. To achieve this, a thorough parametric analysis was conducted to assess the influence of three key parameters: the number of CFRP strip layers, concrete compressive strength, and different size of the opening (600×600 mm).

Each parameter was examined in isolation, with all other

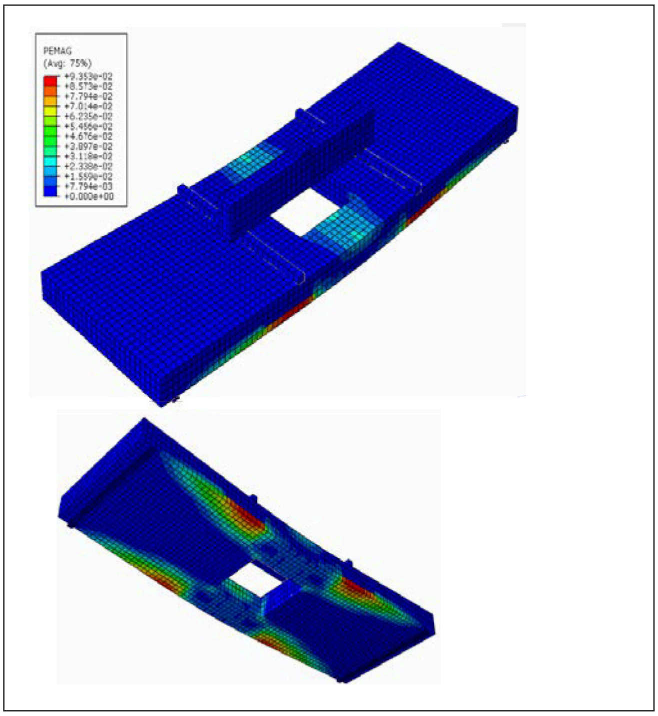


Fig. 9: Plastic strain magnitude of Slab1 at ultimate load

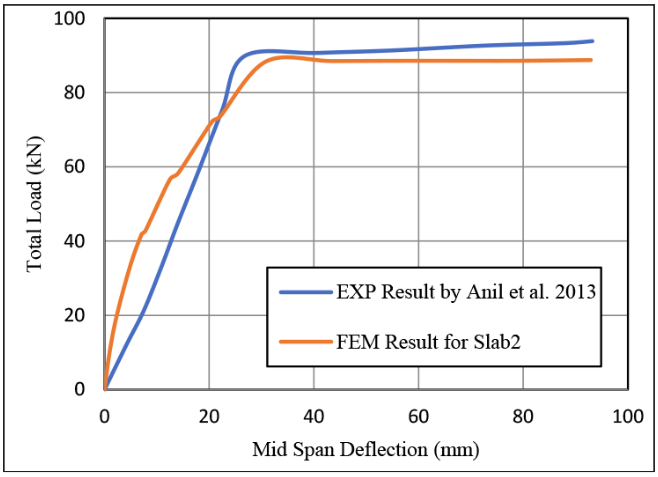


Fig. 10: Exp. and num. load-displacement curve of Slab2 with CFRP strengthening

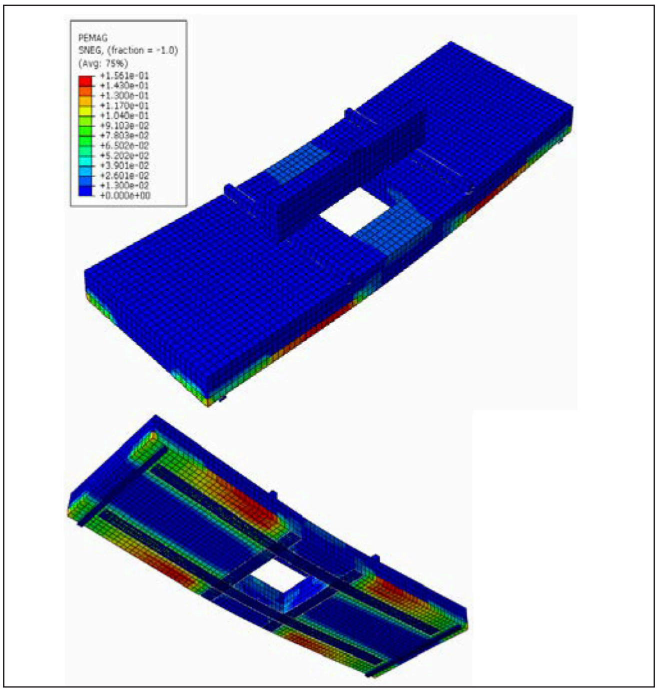


Fig. 11: Magnitude of plastic strain for the specimen Slab2 at maximum load

variables held constant to accurately evaluate the impact of the specific parameter on the behavior of the slab. The numerical tests were designed to comprehensively analyze the flexural behavior of the RC slabs reinforced with CFRP and to gain a deeper understanding of the underlying mechanics of the system. The results of this study will provide valuable insights for the design and construction of reinforced concrete structures that utilize CFRP reinforcement, and will aid in the development of more efficient and reliable structural systems.

4.1 Influence of adding additional layers of CFRP strips

During the actual experimental test, a single layer of CFRP strips was utilized for Slab2. In order to investigate the impact of adding more layers of the CFRP strips on the behavior of Slab2, it was modeled by adding a second CFRP sheet on top of the existing sheet in the finite element analysis, and identified as Slab3. The results obtained from the numerical simulation are presented through the load-deflection curves depicted in *Fig. 12*. These findings provide valuable insights into the effectiveness of using double layers of CFRP and can assist in optimizing the design of reinforced concrete structures with openings.

Alternatively, numerical results demonstrate a clear relationship between the number of CFRP layers and the ultimate load capacity of Slab2. Specifically, as the number of CFRP layers increases from 1 to 2, there is a noticeable increase in the ultimate load capacity. In fact, the increment in ultimate load capacity is approximately 10%, indicating a significant improvement in structural performance. These findings highlight the importance of considering the number of CFRP layers when designing and assessing the load-bearing capacity of reinforced concrete structures.

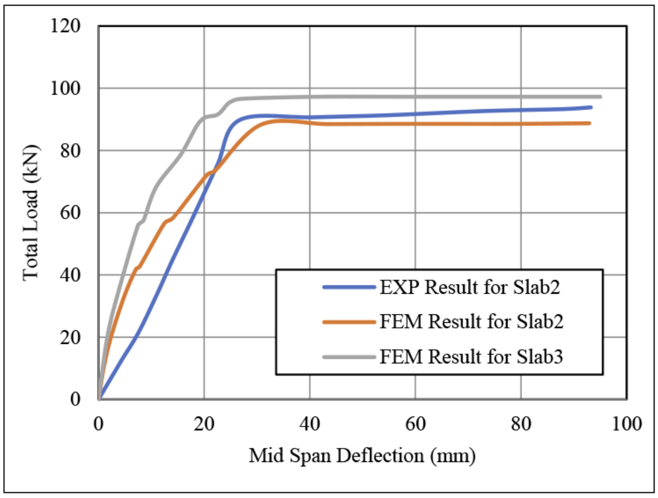


Fig. 12: Load-deflection diagram based on FEM analysis for Slab2 with single CFRP layer compared to Slab3 with double CFRP layers

4.2 Influence of different concrete compressive strength

A parametric study was conducted to investigate the effects of concrete grade on Slab2 performance. The purpose of this study is to assess the precision of the finite element analysis, and it's not intended to reflect realistic conditions, since the compressive strength of the tested slab can not be changed. *Fig. 13* sheds light on how different concrete grades affect the load-deflection response of Slab2. Our study evaluated the

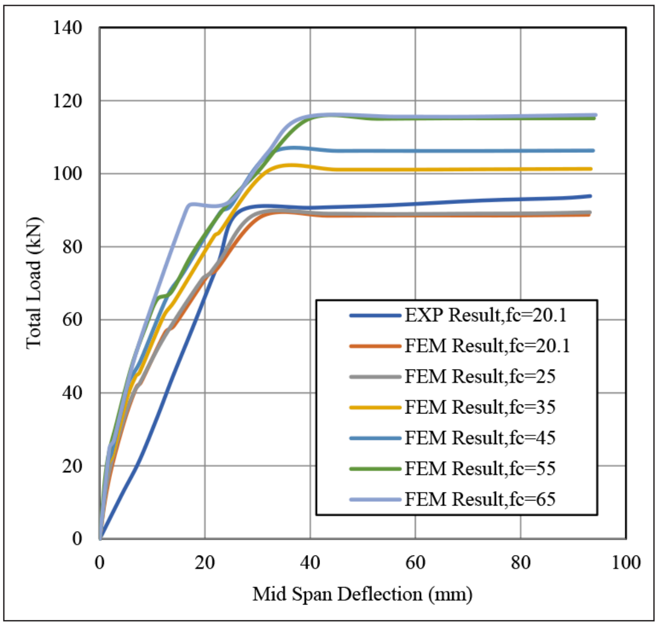


Fig. 13: Influence of concrete compressive strength on the load-displacement curve of the Slab2

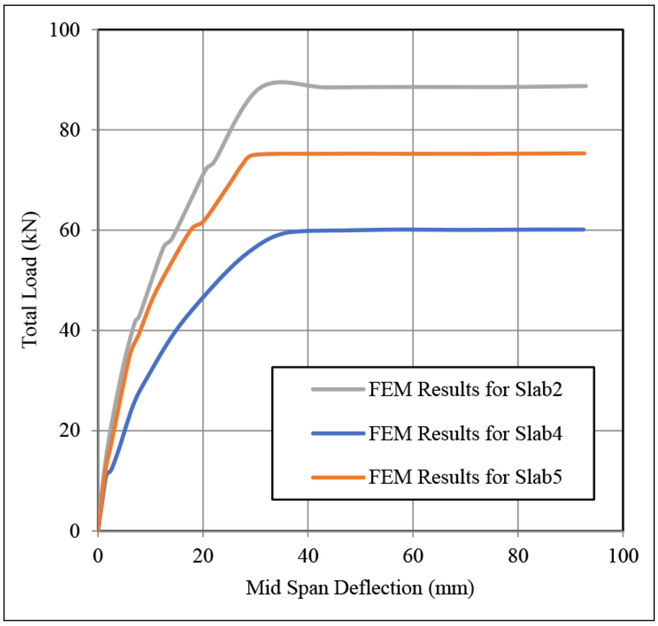


Fig. 14: Load-deflection diagram based on FEM analysis for Slab2, Slab4 and Slab5

impact of five concrete compressive strengths, ranging from 25 to 65 MPa, on the slab's performance. It was observed that as the compressive strength of the concrete increased, so did its ultimate load-bearing capacity as expected.

Compressive strength is the most important parameter of the concrete material, influencing its various other properties, including tensile strength, bending strength, shear resistance, and bond with reinforcement bars. The higher the compressive strength, the better the concrete performs, resulting in up to 30% higher failure loads.

In conclusion, the results of our study highlights the importance of using higher-grade concrete in construction projects, as it leads to improved load-deflection response and general performance of Slab2. Further enhancements are required in the finite element model to accurately capture the debonding failure between the RC slab and the CFRP sheets. Additionally, incorporating the debonding behavior especially into this parametric investigation will yield distinct and more accurate outcomes.

4.3 Influence of different hole sizes

This study analyzed the impact of a larger opening size on the performance of a reinforced concrete slab using FEM modeling. A 600×600 mm opening has been made at the maximum moment region in the model referred to as Slab4 without externally strengthening the opening's edges by CFRP strips, while strengthened one referred to as Slab5, bothspecimens subjected to the same loading conditions, material properties, reinforcement specifications, boundary conditions, mesh density, and CFRP strip thickness as the previously analyzed Slab2.

This section aimed to numerically evaluate the effectiveness of using CFRP strips to strengthen a one-way reinforced concrete slab with a larger opening. Cutting a 600×600 mm hole at the maximum moment region of the reference slab, which was examined in previous experimental work (Anil et al. 2013), will reduce its load-bearing capacity by 44%, i.e., the opening will result in less main reinforcement, so the last will yield at a lower load level. Although applying CFRP strips using the same scheme applied to Slab2, as shown in Fig. 3, on the edges of the opening as a strengthening technic will increase the slab carrying capacity by 25%. It should be pointed out that this strengthening method can restore about one-third (33%) of the original strength of the reference slab that was compromised due to the hole. Moreover, a comparison of the load-deflection curves between Slab2 and Slab4 with different opening sizes, as shown in *Fig. 14,* Indicates that increasing the size of the opening to 600×600mm would result in a reduction of the load-bearing capacity by 15%. These results highlight the importance of proper strengthening techniques in RC slabs with larger openings.

5. CONCLUSIONS

This study aims to investigate the impact of using Carbon Fiber Reinforced Polymer (CFRP) strips on the flexure behavior of Reinforced Concrete (RC) slabs. Utilizing the ABAQUS 6.13 software, numerical simulations were carried out to predict the overall flexural Performance of the strengthened slabs. The use of CFRP on the external surface of RC slabs has been acknowledged as an effective method of enhancing the behavior and strength of these structures. In general:

1. The load-midspan displacement curves from the simulation results match the experimental data for all specimens analyzed in this paper. The ultimate loads obtained through numerical analysis varied from the experimental ultimate loads by 1% to 6%, in other words, this high percentage indicates that the finite element model is sufficiently accurate to produce outcomes that are very similar to those obtained through experimental work.
2. The ultimate load capacity of Slab2 can be affected by the compressive strength of the concrete, as suggested by the numerical simulations. The results demonstrate that a higher concrete compressive strength, such as 65 MPa compared to 25 MPa, can result in a 30% increment in the ultimate load capacity of the slab.
3. The numerical analysis results indicated that adding an extra layer of CFRP strips to Slab2 led to a 10% increase in the ultimate load capacity.
4. The study revealed that when removing a 600×600 mm hole from the middle of the monolithic slab that was previously tested, its load-bearing capacity will decrease

by 44%. This occurs because the hole reduces the amount of tension reinforcement, causing it to fail at a lower load level. However, strengthening the opening edges with CFRP strips will increase the slab›s load-carrying capacity by 25%. Additional research is necessary to determine the precise quantity of CFRP strips needed to completely restore the flexural capacity of slabs with openings to their initial states prior to the removal of the hole.

6. REFERENCES

Al-Amery R, Al-Mahaidi R (2006) Coupled flexural–shear retrofitting of RC beams using CFRP straps. Compos Struct 75:457–464. https://doi.org/10.1016/J.COMPSTRUCT.2006.04.037

Anania L, Badalà A, Failla G (2005) Increasing the flexural performance of RC beams strengthened with CFRP materials. Constr Build Mater 19:55–61. https://doi.org/10.1016/J.CONBUILDMAT.2004.04.011

Anil Ö, Kaya N, Arslan O (2013) Strengthening of one way RC slab with opening using CFRP strips. Constr Build Mater 48:883–893. https://doi.org/10.1016/J.CONBUILDMAT.2013.07.093

Benjeddou O, Ouezdou M Ben, Bedday A (2007) Damaged RC beams repaired by bonding of CFRP laminates. Constr Build Mater 21:1301–1310. https://doi.org/10.1016/J.CONBUILDMAT.2006.01.008

Ceroni F (2010) Experimental performances of RC beams strengthened with FRP materials. Constr Build Mater 24:1547–1559. https://doi.org/10.1016/J.CONBUILDMAT.2010.03.008

Chajes MJ, Thomson TA, Januszka TF, Finch WW (1994) Flexural strengthening of concrete beams using externally bonded composite materials. Constr Build Mater 8:191–201. https://doi.org/10.1016/S0950-0618(09)90034-4

Costa IG, Barros JAO (2010) Flexural and shear strengthening of RC beams with composite materials – The influence of cutting steel stirrups to install CFRP strips. Cem Concr Compos 32:544–553. https://doi.org/10.1016/J.CEMCONCOMP.2010.03.003

Ebead UA, Marzouk H (2004) Fiber-Reinforced Polymer Strengthening of Two-Way Slabs FEM Analysis for UHP-FRC subject blast loading View project Thin Laminated Cement-Based Composites for Rehabilitation and Strengthening Existing Structures View project. ACI Struct J 101:

Esfahani MR, Kianoush MR, Tajari AR (2007) Flexural behaviour of reinforced concrete beams strengthened by CFRP sheets. Eng Struct 29:2428–2444. https://doi.org/10.1016/J.ENGSTRUCT.2006.12.008

Gao B, Leung CKY, Kim JK (2005) Prediction of concrete cover separation failure for RC beams strengthened with CFRP strips. Eng Struct 27:177–189. https://doi.org/10.1016/J.ENGSTRUCT.2004.09.007

Kim HS, Shin YS (2011) Flexural behavior of reinforced concrete (RC) beams retrofitted with hybrid fiber reinforced polymers (FRPs) under sustaining loads. Compos Struct 93:802–811. https://doi.org/10.1016/J.COMPSTRUCT.2010.07.013

Li L, Guo Y, Liu F (2008) Test analysis for FRC beams strengthened with externally bonded FRP sheets. Constr Build Mater 22:315–323. https://doi.org/10.1016/J.CONBUILDMAT.2006.08.016

Rafi MM, Nadjai A, Ali F, Talamona D (2008) Aspects of behaviour of CFRP reinforced concrete beams in bending. Constr Build Mater 22:277–285. https://doi.org/10.1016/J.CONBUILDMAT.2006.08.014

Smith ST, Kim SJ (2009) Strengthening of one-way spanning RC slabs with cutouts using FRP composites. Constr Build Mater 23:1578–1590. https://doi.org/10.1016/J.CONBUILDMAT.2008.06.005

Starossek U, Falah N, Lohning T (2010) Numerical analyses of the force transfer in concrete-filled steel tube columns. Structural engineering and mechanics : An international journal 35:241–256

Toutanji H, Zhao L, Zhang Y (2006) Flexural behavior of reinforced concrete beams externally strengthened with CFRP sheets bonded with an inorganic matrix. Eng Struct 28:557–566. https://doi.org/10.1016/J.ENGSTRUCT.2005.09.011

Wenwei W, Guo L (2006) Experimental study and analysis of RC beams strengthened with CFRP laminates under sustaining load. Int J Solids Struct 43:1372–1387. https://doi.org/10.1016/J.IJSOLSTR.2005.03.076

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