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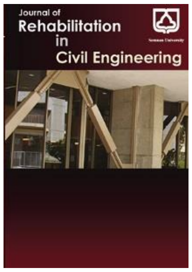

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Improving the Punching Shear Strength of RC Slabs by FRP and Steel Sheets

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ABSTRACT

This paper deals with the modeling of punching shear failure in reinforced concrete slabs using nonlinear finite element analysis. The 3D finite element analyses (FEA) were performed with the appropriate modeling of element size and mesh, and the constitutive modeling of concrete. The FE numerical models are validated by comparing with the experimental results obtained from tested specimens and previous research. One slab served as a control without any modification while three slabs were strengthened. The ultimate behavior of FRP strengthened RC flat slabs under a centrally applied load. Each method of repair or strengthening is reviewed with emphasis on its performance with respect to the application details. The punching shear capacity, stiffness, ductility were investigated. In addition, the analytical results were compared with the predictions using the provision of ACI 318-08. The results showed that for control slab and strengthened specimens an increase varied from 4% to 105% in punching shear capacity is determined.

1. Introduction

Slab-Column or flat slab systems are commonly used in reinforced concrete construction because of their flexibility in architectural appearance and lower cost of their simple formwork. In these systems the slab is supported directly by columns that made them susceptible to the punching shear and floor damage or even substantial structural failure. The shear capacity of slab-column connection can be improved by increasing of slab thickness or using drop panel and column capitals but the increasing of slab thickness causes a cost and dead weight increase or construction difficulties. Therefore, modifying of punching shear resistance needs to some economical and practical alternatives such as installing steel bars or rods, steel jacketing and externally installing CFRP stirrups and sheets. In the past decades several steel-based strengthening options for increasing the punching shear capacity of flat slabs have been developed by some researchers.

Binici et al. [1] studied the use of CFRP stirrups fixed in holes drilled around columns independently for both eccentric and concentric. El-Salakawy et al. [2] investigated the effect of shear bars or shear bolts in the punching strength and the deformation capacity of the connections and ductility due to transferring of the failure mode from the punching to flexural. Esfahani et al. [3] studied the punching shear strengthening of RC flat slabs using CFRP sheets located at the tension side of the slabs. They found that the punching shear strength of slabs can be increased by using of CFRP sheets, in addition to steel reinforcing bars, as flexural reinforcement. Stark et al. [4] investigated the behavior of four slab-column specimens were upgraded by externally installed carbon fiber-reinforced polymer (CFRP) stirrups, they found that the proposed upgrade method is successful in increasing deformation capacity and avoiding brittle failures that can occur under high gravity loadings. El-Salakawy et al. [5] found that the FRP sheets simultaneous to steel bolts can increases the deformation of connections and transferred the failure mode to flexural one.

Nguyen-Minh et al. [6] studied behavior and capacity of steel fiber reinforced concrete (SFRC) flat slabs of different dimensions. In addition, Amen Agbossou et al. [7] studied the experimental and theoretical behavior of slabs strengthened by FRP. The experimental results show that FRP significantly increases punching failure stress, resulting in a reduction of slab rotation around the loading column. The theoretical investigation presents a finite element model for the bending of strengthened slabs. Nguyen-Minh et al. [6] performed an evaluation of accuracy of existing models and formulas in previous studies that used to predict punching shear resistance of steel fiber reinforced concrete (SFRC) that results from the evaluation show that the existing formulas gave inaccurate results with a large scatter in comparison with the testing results. Also, Maya et al. [8] presented a mechanical model for predicting the punching strength of SFRC slabs as well as conventional reinforcement. This model was validated against a wide number of available experimental data and its accuracy was verified.

Metwally [9] evaluates the punching shear strength of RC flat slabs reinforced with different types of FRP. The experimental punching shear strengths were compared with the available theoretical predictions and a number of existing models and two approaches for predicting the punching strength of FRP-reinforced slabs are proposed. Koppitz et al. [10] performed an experimental study of full-scale reinforced concrete flat slabs crosswise strengthened with prestressed CFRP straps against punching shear. They found that, Strap activation and thus strap force increments were higher in cases with either lower prestressing or higher strap stiffness and the deformability of the steel frame allowed a balancing of the strap forces.

Meisami et al. [11] investigated the behavior of two-way flat slabs were strengthened in different ways with an innovative technique of using FRP fans with central loading. It was shown that this method of strengthening can increase the shear capacity of the slab up to a high value around twice of that of controlled slab.

Husain Abbas et al. [12] examined the punching shear and energy absorption of RC slabs strengthened using CFRP sheet and textile reinforced mortar (TRM). Ruiz and Muttoni [13] introduces a physical model based on CSCT that allows one to estimate, on a rational basis, the contributions of concrete and of shear reinforcement to the punching shear strength. Micallef et al. [14] proposed an analytical model on the basis of the CSCT that can be applied to flat slabs subjected to impact loading. This model is particularly useful for cases such as progressive collapse analysis and flat slab–column connections subjected to an impulsive axial load in the column.

The objective of the current study was to explain a proposed finite element model of RC flat slab to examine the application of steel sheets, CFRP sheets and FRP fans on the improving of punching shear and ductility of tested specimens by Meisami et al. [11] through ABAQUS. The results of analytical study can be of interest in evaluating of punching shear failure and strengthening of existing RC flat slabs suffering from low punching shear capacity and select of method led to the best performance. Following the previous studies, in current paper the ability of three existing techniques for improving of punching shear strength of flat slabs was studied. In addition, the analytical results were compared with the predictions using the provision of ACI 318-08 [15].

2. Nonlinear Analysis

In this paper a finite element (FE) analysis is used to investigate the flat slab response and to show how the slab's behavior will change while are strengthened using different methods. The comparison between the results of the analytical model and the experimentally obtained results enables the validation of the performance of the proposed FE model. The FE model are verified and evaluated by experimental results of the study conducted by Meisami et al. [11]. The control slab is a 1200*1200 mm^2 square slab with 105 mm thick and simply supported on the edges and loaded by a hydraulic jack through a 150*150*30 mm steel plate in the center of slab. Fig. 1 describes the dimensions and reinforcement arrangement of original and 3D model of control slab. The proposed model delivered valuable outputs concerning the behavior of the flat slab such as load and the deflection of the slab. Good agreement is noticed between the results of FE model and experimentally results obtained by Meisami et al. [11].

2.1. Finite Element Modeling

The C3D8R element was used to model the concrete Having eight nodes with three translation degree of freedom (Velizy-Villacoublay, [16]), this element can be capable of predict plastic deformation, cracking and crushing of concrete. The steel reinforcement was modeled as T3D2 element with 2 nodes and 3 degrees of freedom in each node. Furthermore, for the modeling of FRP composites an anisotropic material was defined. The behavior of FRP in tension and compression in the principle directions was assigned as bi-linear stress-strain curve. A full compability between FRP and concrete was assumed by joining the node of FRP elements with concrete elements directly without considering the epoxy elastic elements. The overall properties of concrete and assumed materials to strengthen of control slab are given in Table.1.

2.2 Modeling the behavior of concrete

The nonlinear behaviour of concrete is mostly modelled by using smeared crack or damaged plasticity approaches. In the smeared crack concrete model the initiation of cracking occurs when the concrete stresses reach on of failure surfaces either in the biaxial tension region or in a combined tension- compression region. When the confining pressure of concrete is adequately large to prevent of cracking, the brittle behaviour of concrete disappears. The damage of quasi-brittle material such as concrete can be defined by evaluating the dissipated fracture energy required to generate of micro cracks (Widianto [17]).

Table 1. Material property of Steel, Concrete and CFRP in ABAQUS

	CFRP	Concrete	Steel
Elastic Modulus (GPa)	79.94	30	**200**
Poisson Ratio	-	0.2	**0.3**
Tensile Stress (MPa)	925	2.5	**500**
Compressive Stress (MPa)	-	35.4	**500**

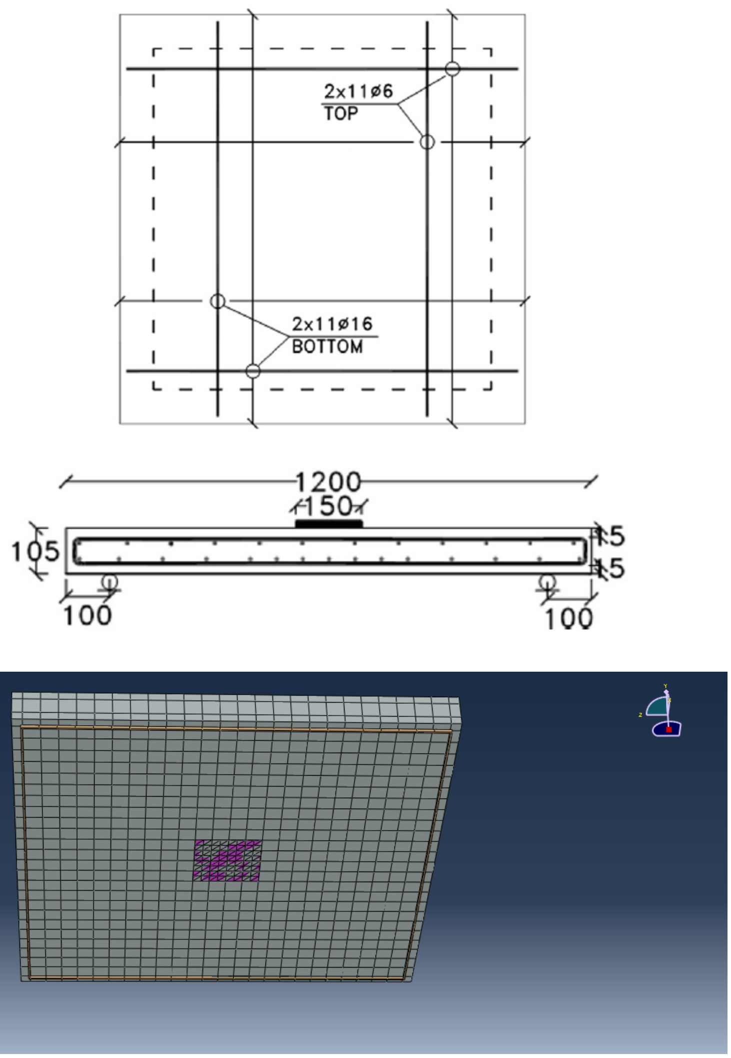


Fig. 1: Dimensions and reinforcement arrangement of Control Slab [11]

The stress-strain curve of concrete was assumed by means of Hognestad model

(Fig.2). The concrete damaged plasticity model uses concepts of isotropic damaged elasticity in combination with isotropic tensile and compressive plasticity to represent the inelastic behavior of concrete and the strain rate is decomposed to two terms of elastic and plastic part of the strain rate. The stress –strain relation is governed by scalar damaged elasticity

$$\sigma = (1 - d)D_{el} \tag{1}$$

Where D_{el}, is the undamaged elastic stiffness of is concrete and d is the scalar stiffness degradation variable which can be assumed zero to one. In current study, the damaged plasticity approach was used for modeling of the behavior of concrete. The material properties are used for C30 grade concrete. In ABAQUS, the selection of tension stiffening properties is important that more tension stiffening makes it easier to obtain numerical solution, but too little tension stiffening will cause the local cracking failure and the instability of overall response of model. Results obtained from this model is verified by experimental results reported by Meisami et al. [11] as shown in Fig. 3. At least, the assumed failure ratios of concrete are described below:

a. *Ratio of ultimate biaxial-to-uniaxial compressive stress was assumed as default value of 1.16.*

b. *Absolute of the ratio of uniaxial tensile-to-uniaxial compressive stress of failure was default being of 0.09.*

c. *Ratio of a principal component of plastic strain at ultimate stress in biaxial compression to the plastic strain at ultimate stress in uniaxial compression default assumed 1.28*

The materials properties refer to modeling of concrete are presented in Table. 2.

Table 2. Mechanical properties of Steel, Concrete and FRP in ABAQUS

Dilatation angle	**Eccentricity**	***fbo/fco***	***κ***	**Viscosity parameter**
36	0.1	1.16	0.667	0

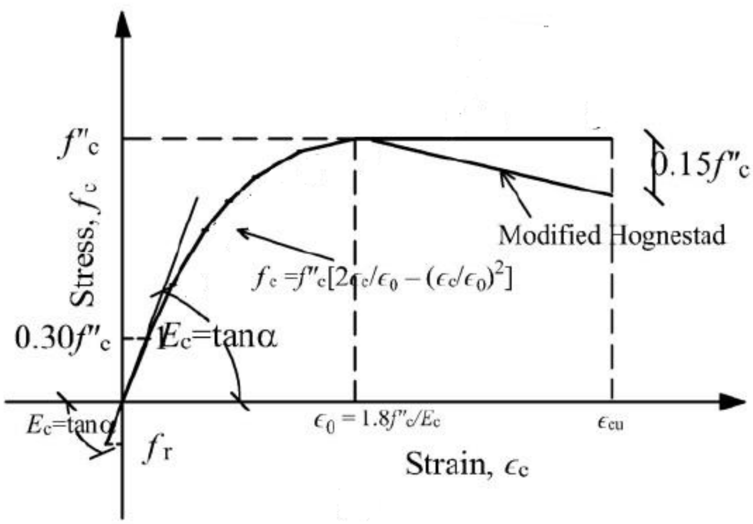


Fig. 2: Stress-strain diagram of concrete

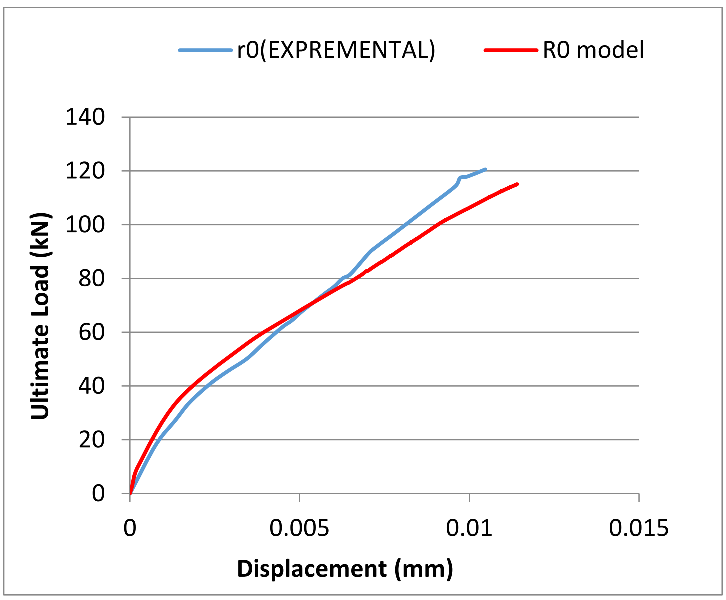


Fig. 3: Comparing of experimental and analytical results

3. Case study on some strengthened flat slabs

As a case study on the punching shear behavior of RC flat slabs strengthened by FRP laminates, a control specimen known as control slab (See Fig.1) strengthened by FRP with various techniques were analyzed. All of slabs were assumed simply supported in four sides and subjected under monotonic loading applied on the center of the slab through a thick steel plate with dimension of 150*150*30mm.

This study aims at investigating RC slabs strengthening by different methods to increase the shear capacity of control slab suffering from low punching shear capacity. In order to strengthen of the investigated control slab, three general techniques were considered as follows:

a) Steel sheets installed around the column or loading region

b) CFRP laminates bonded around the column or loading region

c) FRP fans; in this technique, the drilled holes were assumed at the defined points on the slab around the loading region, then the rolled FRP material is anchored in to the holes like a FRP shear stud [11]. The configuration of holes were referred to as types A, B, C and D as shown in Fig. 4.

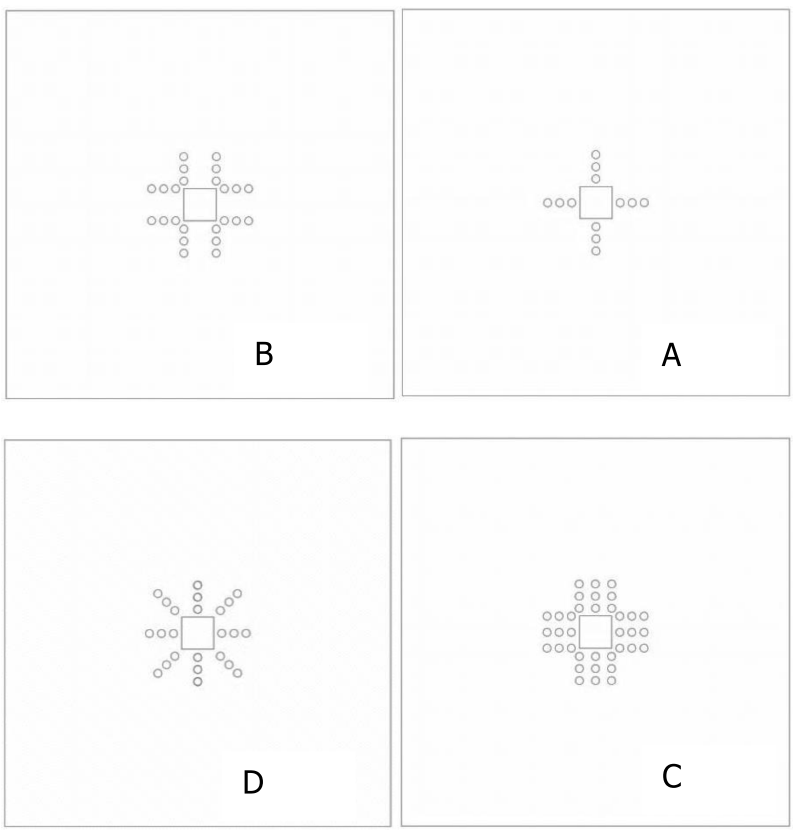


Fig. 4: Various type of FRP Fan technique

4. Analysis of Strengthened slabs

4.1. Load –displacement curve of slabs strengthened by steel sheets

Load - displacement variation of slabs strengthened by steel sheet are shown in Fig. 5, these curves are compared together and to the control slab. In this series, the strengthened slabs were named according to the area of strengthening steel plate. The general naming format is Rxx-t, where, xx and t are the dimension (in **mm**) and the thickness of installed square CFRP sheet (in **cm**) respectively As seen that, with increasing of steel plate area, shear capacity increases and shows greater initial stiffness. Ductility factor is defined as the ratio of Δu to Δy; where Δu is the ultimate central displacement of the slab at maximum load (P_u), and Δy is the similar displacement when the first rebar starts to yield at yield load (P_y).The maximum load capacity obtained for R-50-5, as an increased capacity about 30% is observed in this model compared with control slab. According to Table 3, a constant decreasing of ductility is seen and the ductility of slabs is increases generally due to using of strengthening steel plate. As seen in Fig. 5 no meaningful change in the failure mode of strengthened slabs were observed. In fact, in all modeled specimens, the shear flexural failure mode is observed.

The effect of increasing steel plate thickness on the obtained peak load, deflection at failure and the normalized strength value are presented in Table 4. It is clear that the initial stiffness was not affected by this parameter.

The increase in the ultimate strength of the strengthened slabs is basically due to created capacity with steel plate. It is important that, although, installing of square steel plate can significantly improve the punching shear capacity, but cannot shift the failure mode to the deformable one.

According to the variation of normalized strength of slabs versus the thickness and width of steel plate, it is resulted that, the addition of steel plate volume led to an increase in the normalized shear strength, stiffness and ductility of strengthened slabs, but the thickness is more effective than width of plate. The thick plate (t=10 mm) demonstrated better improving effect than other thin plate.

4.2. Load –displacement curve of slabs strengthened by CFRP sheets

The applied load versus vertical displacement for the specimens of this series is shown in Fig. 6, in the naming format (Rxx-t), xx and t are the dimension (in **mm**) and the thickness of installed square CFRP sheet (in **cm**) respectively, as can be seen in Fig. 6, the general response and behavior is similar to that of previous ones and specimens strengthen with steel plates generally showed greater stiffness and higher peak load in comparison with their similar specimens strengthen with CFRP sheets.

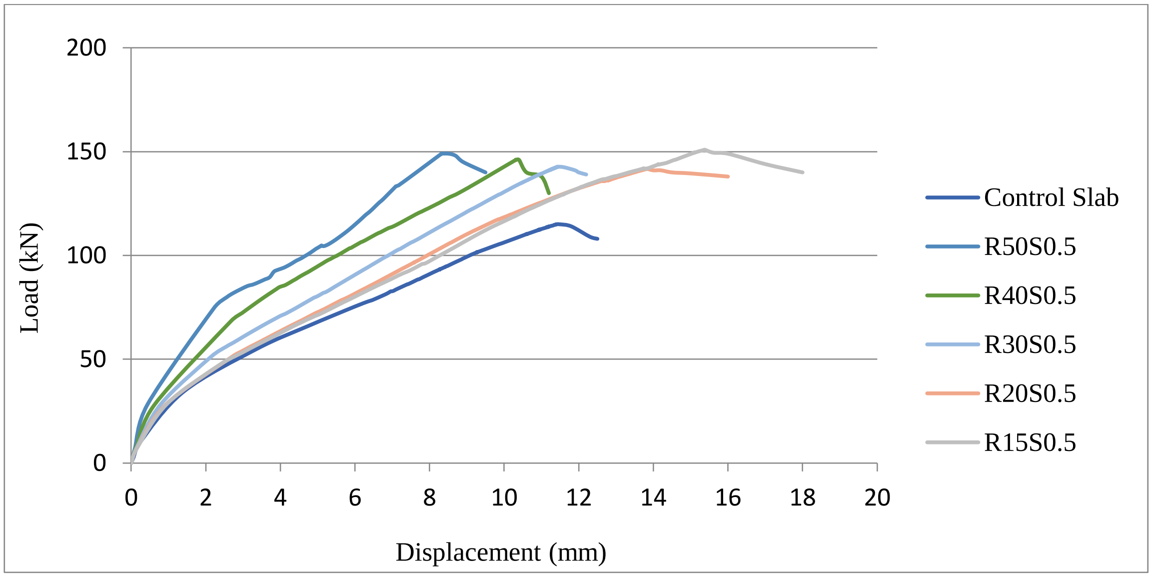


Fig 5: Load – Displacement curves of Steel Plate strengthening technique

Table 3. Ultimate Load and ductility of Steel Plate strengthening technique

Model	Ultimate Load P_u (kN)	P_u(%)	P_u/P_{ACI}	Ductility	Ductility Increment (%)
CONTROL MODEL	115.01	-	1.04	10.17	-
R15S0.5	148.52	129.1	1.35	8.14	25
R20S0.5	141.73	123.2	1.29	8.74	7
R30S0.5	142.73	124.1	1.30	8.37	2.8
R40S0.5	146.11	127.04	1.33	8.83	8.4
R50S0.5	149.04	129.58	1.35	8.79	8

Table 6 presents the specimen responses in terms of the calculated punching shear load and the normalized shear strength by the measured shear capacity according to the ACI building code [15]. It is cleared that the addition of fibers sheets led to an increase in the ultimate shear strength of slabs but the initial stiffness is not affected by the presence of CFRP. The results from the obtained shear capacity are a clear indication that the presence of CFRP sheets allowed the slabs to develop their ultimate shear strength prior to punching. It is necessary to note that, this increase in punching shear strength may translate into a change in failure mode from brittle punching shear to ductile flexural failure. Comparing slabs strengthen with CFRP and GFRP, the specimens with GFRP had higher punching shear capacities due to higher ultimate tensile strength. In addition, the GFRP sheets demonstrated larger strains and deflection due to lower modulus of elasticity in comparison with CFRP sheets.

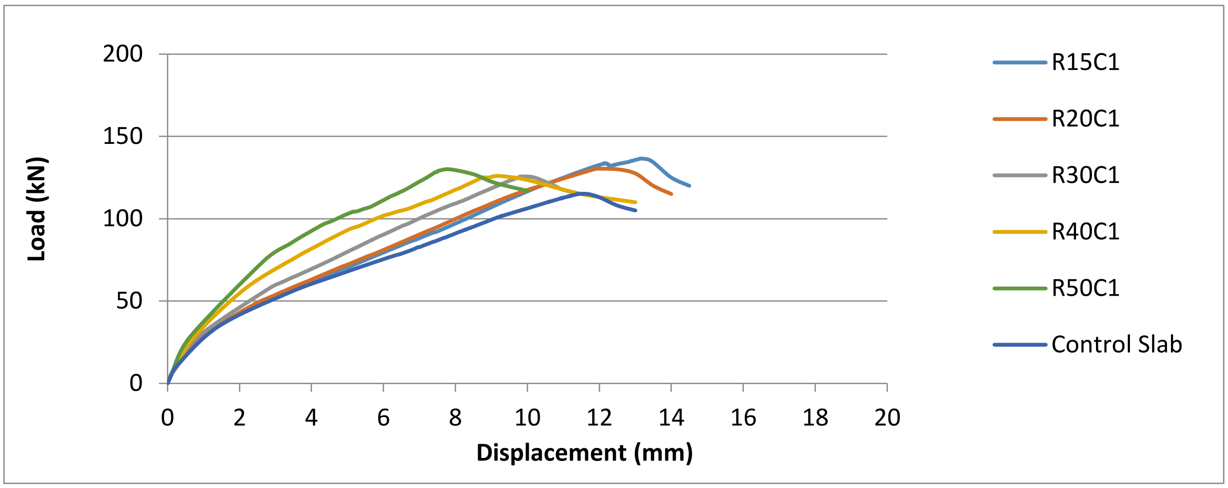


Fig 6: Load – Displacement curves of CFRP Sheet strengthening technique

Table 4. Ultimate Load and ductility of Steel Plate strengthening technique with various areas

Model	Ultimate Load P_u (kN)	P_u(%)	P_u/P_{ACI}	Ductility	Ductility Increment (%)
CONTROL MODEL	115.01	-	1.04	14.7	-
R15C1	136.57	1.18	1.24	13.4	65
R20C1	130.41	1.13	1.19	12.5	54
R30C1	125.66	1.09	1.14	11.5	41
R40C1	126.79	1.10	1.15	11.9	47
R50C1	129.27	1.12	1.18	11.8	45

4.3. Load –displacement curve of slabs strengthened by FRP fan

The last studied method for strengthening of a flat slab is using thin FRP materials which are anchored at their ends on the slab similar to a fan that is named FRP fan. In this method four different pattern of FRP grids were assumed in order to strengthening of

RC slabs that provided constructive steps for strengthening are as follows in Fig. 7.

a. Drilling the holes at predefined points.

b. The FRP fans crossed through the holes.

c. Two outer ends of the fans are spread on the bottom and top of slab like a fan.

In Fig. 9, the load-displacement curve of slabs strengthened by four different pattern (a, b, c & d) and corresponding control slab are shown. Comparison the results of the control slab and strengthened slabs show a considerable increase in the ultimate strength of slabs. In Table 7 the calculated ultimate loads are normalized by a capacity of the control slab and the provided shear strength by ACI318-08; As shown, the significant increase in the normalized shear capacity is varied from 40% to 95% compared with control slab, the maximum increase is observed in the strengthen slab with pattern D with a shift in the ultimate displacement from 11.4 to 13.8 mm as compared with control slab.

Using the pattern D, C of the holes arrangement (24FRP fan) caused an increase in the punching shear capacity about 95% while the ultimate displacement of strengthened slab with pattern C is remained due to strengthener. It signifies the efficiency of the arrangement of the strengthener FRP fans in increasing the shear capacity and stiffness of slabs as the strengthen slab with pattern C has higher stiffness in comparison with other strengthen slabs and control slab. Despite brittle behavior of the FRP materials, using the fan FRP as strengthener of slabs, not only increases the shear capacity but also can shift the failure mode to deformable one as demonstrated in Table 5. Fig. 8 shows the meshing of this series of strengthened slabs.

Fig. 7: Repair and strengthening process using FRP fan technique [11]

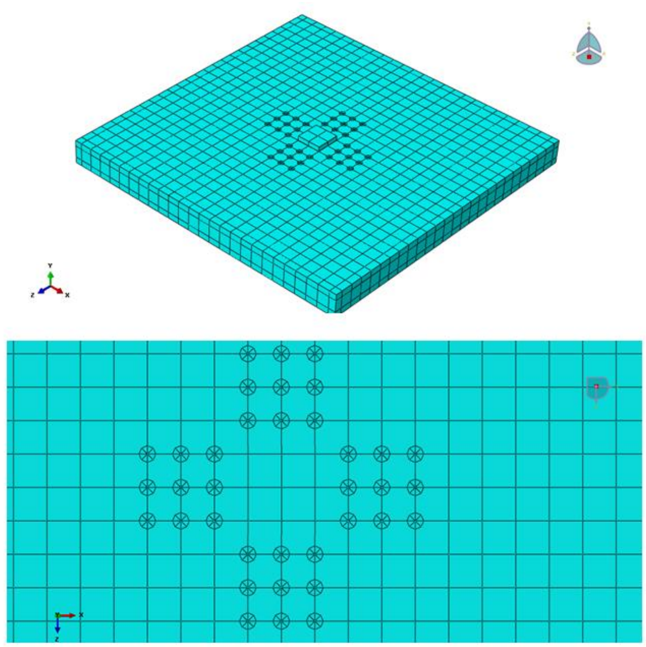


Fig. 8: Modeling of slabs strengthened by using of FRP fan technique

Table 5. Ultimate Load and ductility of CFRP Fan strengthening technique

Model	Ultimate Load P_u (kN)	P_u(%)	P_u/P_{ACI}	Ductility	Ductility Increment (%)
CONTROL MODEL	115.01	-	1.04	7.14	-
A-CFRP	162.49	1.41	1.48	8.98	26
B-CFRP	193.02	1.67	1.76	8.28	16
C-CFRP	220.83	1.92	2.01	8.25	15.5
D-CFRP	224.64	1.95	2.05	9.87	38

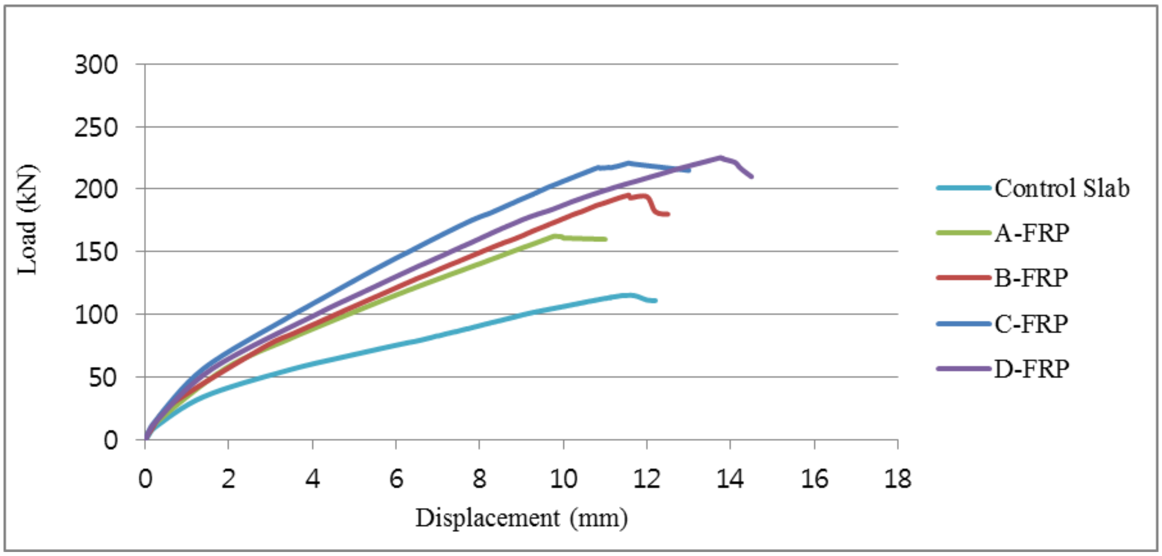


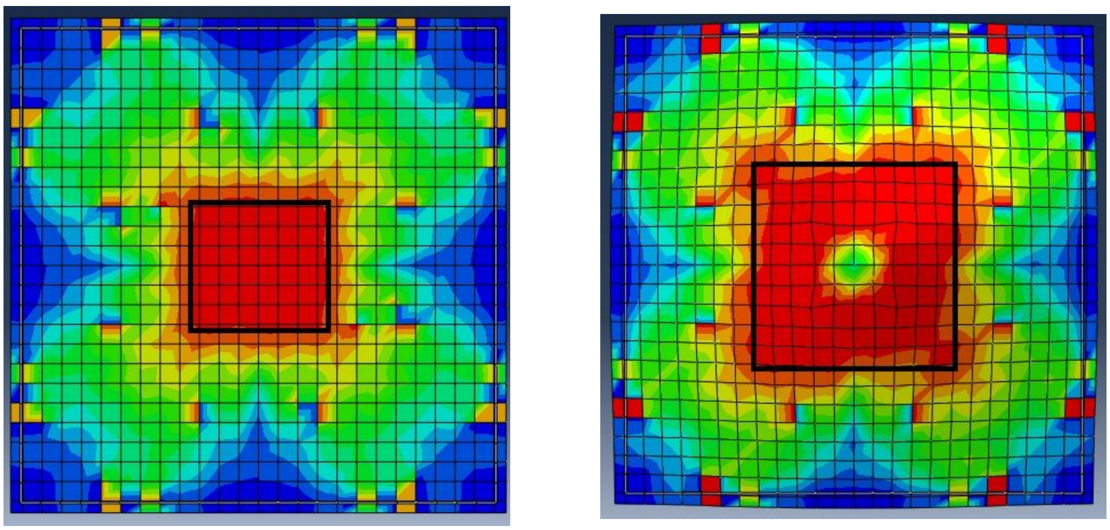
Fig. 9: Load – Displacement curves of CFRP Fan strengthening technique

5. Comparison of result of three strengthening Method

As shown in past section, all the flat slabs failed in the classical punching mode exhibited an abrupt punching shear that an immediate and significant drop in load was observed at peak point. Slabs strengthen with CFRP or GFRP sheets had lower punching strength compared with slab strengthen with steel plates.

Slabs strengthen by FRP fans in comparison with strengthen slabs by GFRP sheets have higher punching shear capacities and stiffness. In Fig. 10, the outline of the extent of punching failure in each series of strengthen slab and control slab is presented by bold line. The slabs failed along a sloping surface extending from the loading zone of slab. The shear failure plan is affected by the method of strengthening of slabs. It is cleared from this Fig that, in strengthen slabs by using of FRP fan, the punching shear failure plan surfaced at a greater distance from the loading zone.

The results of strengthened slabs are compared on the basis of American concrete code, ACI 318-08 that predicts lowest amount of the concrete punching shear capacity for the investigated slabs. The summary of the results as shown in Table 3, 4 and 5 shows the increase percent in the shear capacity of the strengthened slabs compared to the predicted loading capacity of un-strengthened slabs based on the code.



a b

Fig. 10: Damage parameter contour of all strengthening patterns (a: control slab, b: strengthened slab by steel sheets)

6. Conclusions

In this study, the punching shear capacity of slabs strengthened by three different methods was studied. One slab was used as control and other specimens were strengthened. The following conclusions may be drawn according to the results obtained from the investigations.

- The nonlinear finite element analyses (FEA) can be used to investigate the punching shear strength in flat slabs strengthened by various techniques, leading to a good agreement when comparing to existing test results.
- Comparison of the results of tested slabs shows the considerable capability of strengthening of concrete; while the FRP Fans is used, the higher punching shear capacity is maintained in comparison with those strengthened by CFRP or steel sheets.
- Using the FRP sheets led to a decrease in the shear capacity and/or ductility of slabs but the initial stiffness is not affected by the

presence of FRP. This increase in punching shear strength may translate into a change in failure mode from brittle punching shear to ductile flexural failure.

- In the pattern D, C of the holes arrangement (24FRP fan) resulted an increase in the punching shear strength of 95%. The increasing of the shear capacity and the stiffness of slabs are affected by the arrangement of the strengthener FRP fans.
- All the flat slabs failed in the general punching mode exhibited an abrupt punching shear with an immediate drop in load was observed at peak point. Slabs strengthen with CFRP or GFRP sheets had lower punching strength compared with slab strengthen with steel plates. This was due to higher strength of steel.
- The shear failure plan depends on the method of strengthening that in strengthen slabs by using of FRP fan, the punching shear failure plan surfaced at a greater distance from the loading zone.
- The results of this study were compared with punching shear predictions of concrete slabs based on ACI 318 codes. The results showed that for control slab and strengthened specimens an increase varied from 4% to 105% in punching shear capacity is determined.

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