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Strengthening of Two-way RC Slabs with Central Opening

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Abstract

Although creating an opening in an existing Reinforced Concrete (RC) slab is permitted under specific circumstances, it may lead to a weakened slab. To investigate the strengthening of two-way RC slabs with an opening, six full-scale two-way RC slabs with a central opening, in addition to one reference slab without opening, were tested up to failure under monotonic and cyclic loading. These six slabs consisted of one control un-strengthened slab and five strengthened slabs. The strengthening methods used in this study were either Externally Bonded Glass Fiber Reinforced Polymer (EB-GFRP) or embedded extra steel bars at the tension side of the slabs, as proposed by ACI 318-14 (2014). Failure modes, cracking patterns, ultimate loads, and load -deflection relationships of all slabs are reported. The test results show that using GFRP strengthening method could increase the ultimate strength and flexural stiffness of the slabs significantly. Moreover, embedding extra steel bars around the opening as proposed by ACI 318-14 (2014) may not enhance the load-carrying capacity of the slab to the value of the continuous slab. The test results also show that the deflections of the strengthened slabs with opening under service loads are more than that of the slab without opening.

Keywords: *Externally Bonded Glass Fiber Reinforced Polymer (EB-GFRP), GFRP sheet, opening, RC slab, strengthening*

1. Introduction

Openings are installed in existing Reinforced Concrete (RC) slabs because of facility requirements such as the installation of elevators, escalators, stairs, air conditioning, piping ducts and fire-extinguishing systems. Smith and Kim (2009) and Kim and Smith (2009) realized that although these openings are necessary in such slabs, they place a break in the continuity of the slab and reduce the load-carrying capacity, stiffness, energy dissipation capacity, and ductility of the slabs. Therefore, an effective strengthening method should be adopted to increase the shear and flexural capacities of the slab with the opening. One of the traditional approaches for strengthening slabs with openings is embedding equal steel bars at the edge of the opening. ACI 318-14 (2014) recommends that in the area common to intersecting middle strips, openings of any size shall be permitted (Fig. 1), provided the total amount of reinforcement required for the panel without the opening is maintained. Therefore, half of the reinforcement interrupted must be replaced on each side of the opening. Using additional steel bars at the opening edges of an existing slab is totally cumbersome and even impossible. ACI 440.2R-08 (2008) recommends that a possible simpler way to strengthen existing RC slabs with openings is bonding Fiber Reinforced Polymer (FRP) sheets to the tension side of the slab around the opening.

Seim *et al.* (2001) concluded that externally bonded fiber reinforced polymer composite strips at the tension side of slabs could increase load capacity up to 370%. However, the overall response of the strengthened slabs changes from the ductile failure to a more sudden failure. The test results showed a significant increase in the repaired slabs strength to an average increase of more than 540% of the original capacity of the control slabs. Using FRP systems for retrofitting applications resulted in an appreciable upgrade of the structural capacity of the as-built slabs up to 500% for unreinforced and 200% for steel reinforced slabs. Mosallam and Mosalam (2003) asserted that in all cases, the failure was preceded by large deformations, which provided a visual warning before ultimate failure. Robertson and Johnson (2004) and Limam *et al.* (2005) showed that CFRP (Carbon Fiber Reinforced Polymer) strips applied to the tension side of RC slabs increased the punching shear strength of the slabs notably.

Arduini *et al.* (2004) presented an experimental research of one-way RC slabs strengthened with externally bonded unidirectional CFRP subjected to two cycles under simply supported conditions. They concluded that the load-carrying capacity can be increased up to 122% in comparison with the reference slabs and this effect is very sharp for slabs with low steel reinforcement ratio. Moreover, different failure modes of slabs with external CFRP laminates were observed such as concrete shearing, concrete crushing, CFRP rupturing, and CFRP peeling. Ebead and Marzouk (2004) assessed the use of CFRP and GFRP

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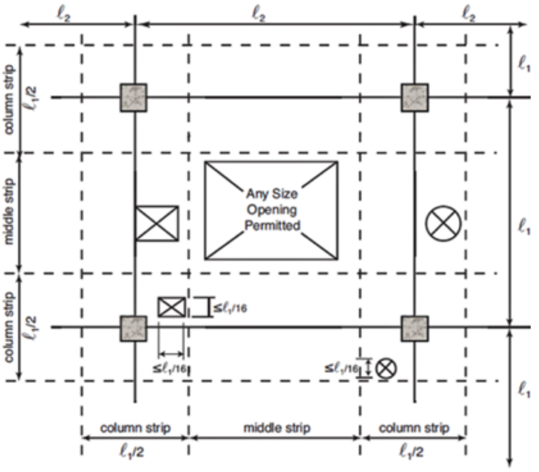


Fig. 1. ACI 318-14 Suggestion for Opening Sizes and Locations in Flat Slabs ($l_2 \ge l_1$)

composites to strengthen two-way simply supported slabs, experimentally. All specimens were centrally loaded and their corners were free to lift. These authors concluded that flexural strengthening slabs using CFRP strips and GFRP laminates led to an average gain in the load capacity of approximately 40% and 31% over that of the reference slabs, respectively. A decrease in ductility and energy absorption was also recorded.

Casadei *et al.* (2004) studied the strengthening of two-way RC slabs with openings and found that anchoring the CFRP resulted in a higher capacity than the situation without anchoring. Enochsson *et al.* (2007) compared strengthened homogeneous slabs and slabs with openings. All strengthened slabs showed a considerably higher load-carrying capacity than the homogeneous slab. The load-carrying capacity of the CFRP strengthened slabs was increased within a range of 24%–125% compared to that of the un-strengthened slab, and 22%–110% compared to the homogeneous one. They also reported the results of tests on FRP-strengthened two-way spanning simply-supported slabs with openings subjected to a uniformly distributed load applied around the opening. They observed that the slabs with the larger openings had a considerably higher load-carrying capacity and a stiffer load -deflection response than the slabs with the smaller ones, because the slab with the large opening behaves closer to a beam than a slab. A yield line method of analysis was also employed in their study. Afefy and Fawzy (2013) concluded that the slabs behaved linearly up to the cracking load and thereafter the load -deflection curve began to increase nonlinearly until the point of the ultimate load-carrying capacity, and then started decreasing rapidly because of a sudden rupture of the CFRP sheets. In an un-strengthened slab, by further loading after the cracking load, the yielding of the internal steel reinforcement occurred. Externally Bonded Glass Fiber Reinforced Polymer (EB-CFRP) technique is very effective in restoring the load-carrying capacity and increasing stiffness of slabs with the opening. Their results showed that the introduced opening reduced the initial stiffness (the slope of the first part of the load -deflection curve) of the slab by about 15% in the elastic range of loading.

In the present research, we implement an experimental study on GFRP strengthened RC slabs with opening subjected to monotonic and cyclic loading. The effect of strengthening using additional steel bars is also accomplished. The required amounts of GFRP sheets and extra steel bars were evaluated under ACI 440.2R-08 (2008) and ACI 318-14 (2014) codes, respectively. The deflection of slabs with the opening is also investigated. ACI 318-14 (2014) provisions do not require special consideration for deflection of slabs with the opening. Finally, we accomplish a comprehensive comparison of ultimate strength and deflection between all slabs with different reinforcement ratios and strengthening methods subjected to different loading types.

2. Experimental Program

2.1 Test Specimens

The experimental program consisted of seven two-way RC slabs. Two un-strengthened slabs consisted of one reference slab without opening and one control slab with an opening. The remaining slabs are with central opening strengthened with either GFRP-sheets or steel bars along the tension side of the slabs around the opening sides. Two out of these five specimens were reinforced internally with different steel bar diameters. All specimens were rectangular in cross-section and simply supported along all four edges. They all had the same dimensions of 1,800 mm × 1,800 mm × 90 mm. The clear span (distance between supports) was 1700 mm for all slabs. A central square opening with a side dimension of 600 mm was devised for each specimen with the opening. This opening size corresponds to the recommendation of ACI 318-14 (2014) for slab opening in the intersection of middle strips. In all slabs, 12 steel bars were spaced at 160 mm centers in each direction. Steel bar spacers at the bottom of the formworks were used to maintain the correct bottom cover of 25 mm for slabs. Five slabs were reinforced with 10 mm diameter steel bars in each direction, while the remaining slabs were reinforced similarly with 14 mm diameter steel bars. The flexural reinforcement ratios in RC slabs with 10 mm and 14 mm bar diameter were 0.87% and 1.77%, respectively. These values are less than the maximum allowable value under ACI 318-14 (2014). All specimens were cast from one concrete mixture at the same time. The cross-section, reinforcement details, and strengthening schemes for the strengthened slabs are shown in Fig. 2.

The calculations of GFRP sheets were based on the loss of steel reinforcement in the opening area. Therefore, the number of GFRP sheet layers used to strengthen the specimens with various reinforcement ratios was different. The EB-GFRP sheets were adopted for strengthening the specified slabs by bonding the GFRP sheets to the tension side of the slabs around the opening sides. The amount of GFRP sheets needed for each slab was calculated under ACI 440.2R-08 (2008). These slabs were strengthened by two or four layers of the GFRP sheets (Fig. 2).

The central opening in slabs interrupted four steel bars in each direction. Thus, each such a slab needed to be strengthened by two steel bars on each side of the opening. The nomenclature, characteristics, and test objectives of all slabs are shown in Table 1.

All specimens were cast in metal molds, simultaneously. During the curing period, all specimens were covered by wet burlap and nylon sheets. Two weeks after casting, the standard cylinders and the specimens were extracted from the molds. After about two months, in order to improve the bond between GFRP sheet and concrete, the concrete substrate was graded and then the surface was cleaned before applying the GFRP. The adequate pressure was applied to the GFRP layers to expel the excess resin and eliminate bubbles from the joint. The application of GFRP sheet and epoxy resin was performed in accordance with the FRP system manufacturer recommendations. Fig. 3 shows one of the GFRP-strengthened slabs.

2.2 Material Properties

The concrete was designed to give an average cylinder compressive strength of 30 MPa. The cylinders had 150 mm diameter and 300 mm height. They were kept in the same conditions with the main seven specimens. The mean value of the compressive strengths of concrete was 30.7 MPa.

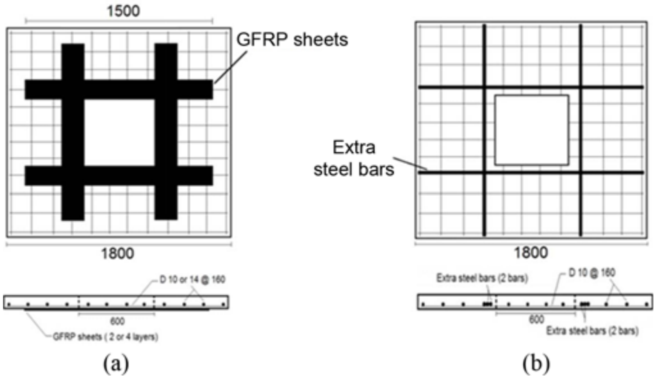


Fig. 2. Strengthening Details: (a) GFRP Strengthened Slabs, (b) Steel Bars Strengthened Slab

Uniaxial tensile tests of two bar sizes were performed to obtain the mechanical properties of 10 mm and 14 mm diameter steel bars according to the ASTM A370-08a (2008). The average yield strength, ultimate strength, and modulus of elasticity were measured as 500 MPa, 650 MPa, and 200 GPa, respectively.

In this study, glass fiber fabric Kor-GFW920 and epoxy resin EPIKOTE 828 were used. The mechanical properties of GFRP fabric sheet and epoxy resin were provided by the manufacturers (Table 2).

2.3 Test Setup, Procedure, and Instrumentation

The load was applied through a 500 kN hydraulic jack. The applied loads were measured by a load cell of 500 kN capacity. Four Linear Variable Differential Transducers (LVDTs) were

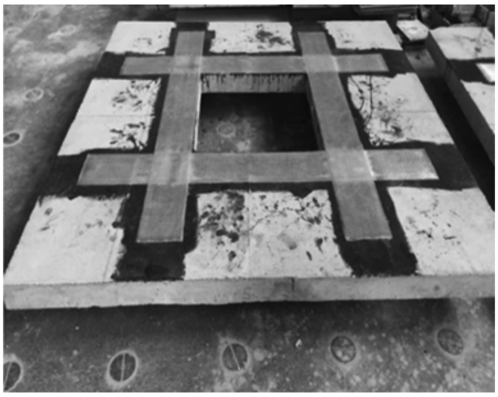


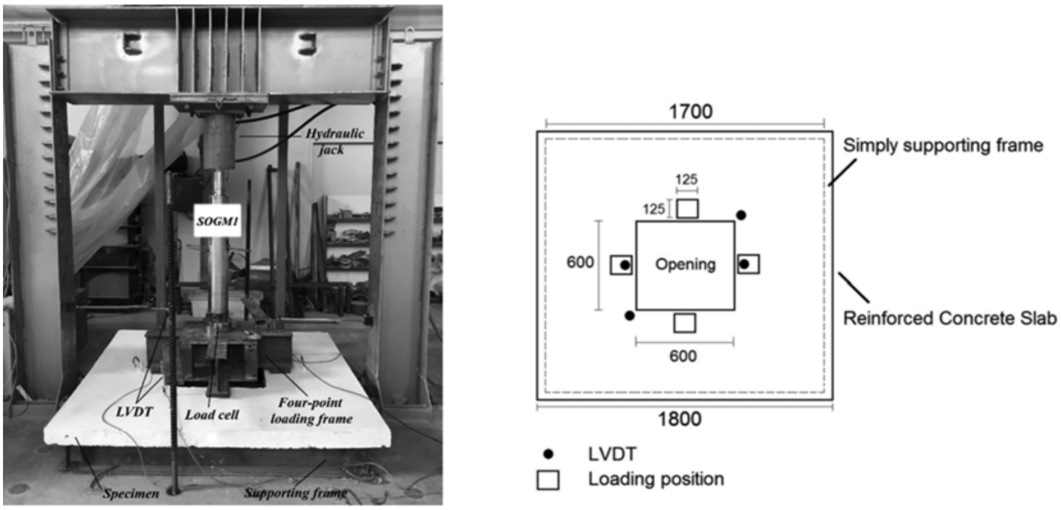
Fig. 3. One of the GFRP-strengthened Slabs

Table 2. Mechanical Properties of GFRP Composites

	GFRP sheet	Epoxy resin
Tensile strength (MPa)	2,300	69
Modulus of elasticity (GPa)	76	2.75
Shear strength (MPa)	-	41
Failure strain (%)	1.50	-
Area weight (g/m^2)	920	-
Thickness (mm)	0.35	-

Table 1. Nomenclature, Characteristics, and Test Objectives of Slabs

Slab	Characteristics	Reinforcement ratio	Objectives
SM	An un-strengthened slab without opening (reinforced by 10 mm steel bars)	0.87%	Reference slab
SOM	An un-strengthened slab with central opening (reinforced by 10 mm steel bars)	0.87%	Control slab
SOGM1	A slab with central opening strengthened by EB-GFRP sheets subjected to monotonic loading (reinforced by 10 mm steel bars)	0.87%	Effect of strengthening using EB-GFRP sheets
SOGC1	A slab with central opening strengthened by EB-GFRP sheets subjected to cyclic loading (reinforced by 10 mm steel bars)	0.87%	Effect of cyclic loading
SOGM2	A slab with central opening strengthened by EB-GFRP sheets subjected to monotonic loading (reinforced by 14 mm steel bars)	1.77%	Effect of reinforcement ratio
SOGC2	A slab with central opening strengthened by EB-GFRP sheets subjected to cyclic loading (reinforced by 14 mm steel bars)	1.77%	Effect of cyclic loading and reinforcement ratio
SOSM	A slab with central opening strengthened by embedded extra steel bars subjected to monotonic loading (reinforced by 10 mm steel bars)	0.87%	Effect of strengthening using extra steel bars



(a) (b)

Fig. 4. Test Setup: (a) Photographic View, (b) Schematic View

Table 3. Test Results

Slab	$P_{cr}(kN)$	$P_u(kN)$	Δ_u (mm)		Failure mode
			Opening corner	Middle of opening side	
SM	207.9	260.1	32.4	52.2	Flexural
SOM	127.5	157.0	43.7	62.3	Flexural- punching shear
SOGM1	210.9	229.7	32.3	47.0	GFRP debonding-punching shear
SOGC1	96.8	218.3	37.7	49.3	GFRP debonding-punching shear
SOGM2	226.6	251.8	22.3	37.2	GFRP debonding-punching shear
SOGC2	98.1	226.4	27.0	38.2	GFRP debonding-punching shear
SOSM	131.2	182.5	29.2	39.8	Flexural-punching shear

Note: P_{cr} = cracking load at the compression (top) face, P_u = ultimate load, Δ_u = deflection at ultimate load

placed on concrete compression surface at the corner and middle of the opening opposite sides such that to measure vertical deflection. A laser and 100 mm LVDTs were used in order to measure the vertical deflection at the middle of the opening opposite sides. Moreover, a 150 mm and 100 mm LVDTs were set at the corners of the openings to measure the vertical deflection at these points. They were positioned at 50 mm from the slab opening sides. A computer- aided data acquisition system was used to automatically record all output data. Fig. 4 shows photographic and schematic views of the test experimental setup. The locations of LVDTs and load positions on the concrete compression side are also shown schematically (Fig. 4).

A special loading frame was used to apply a four-point loading by four special rubbers. The rubbers were 125 mm × 125 mm in dimensions and placed in the middle of four sides of the opening. The space between the rubber centers and the opening edges were 100 mm. RC slabs were simply supported along all four edges by a steel frame to provide a line support distance of 50 mm from the slab edges.

Two different types of loading, monotonic and cyclic loading, were applied. The specific specimens under monotonic loading were loaded until the failure. After identifying the ultimate strengths of these slabs, the specified specimens were tested under cyclic loading. An initial load almost corresponding to 30% of the ultimate strengths of the similar slabs under monotonic loading was first applied. Then, the slabs were loaded cyclically up to the failure. Cyclic loading was applied on slabs with the increments of about 500 N. The initial load on these slabs represents the dead load on slabs since this loading is applied prior to any vertical live load. In all cases, the loading rate was about of 0.25 kN/s.

3. Experimental Results

The test results of the reference, control, and strengthened slabs are compared to determine the effectiveness of each strengthening technique that was adopted to increase the stiffness and load-carrying capacity reduced by introducing the central opening. All strengthened slabs have shown higher stiffness and load-carrying capacity than the control one (SOM). However, these specimens have not reached the strength of the reference slab without opening (SM).

3.1 Ultimate Load

The test results are given in Table 3. The cracking loads, ultimate loads, deflections at ultimate loads and failure modes are reported in this table.

As can be seen from Table 3, the specimen without opening (SM) has the maximum ultimate strength and the un-strengthened slab with an opening (SOM) exhibits the lowest load-carrying capacity among all slabs. As shown in Table 3, strengthening the slabs with an opening by either extra steel bars (SOSM) or GFRP sheets (SOGM1) does not enhance the ultimate strength to the value of the slab without opening (SM). However, using the additional steel bars based on ACI 318-14 (2014) is not as effective as using GFRP sheets to strengthen the slabs with a central opening by increasing the ultimate load-carrying capacity. The GFRP-strengthened slab with an opening (SOGM1) has an ultimate capacity of 88% of the reference slab (SM). In comparison, the slab strengthened with extra steel bars (SOSM) showed 70% of the ultimate capacity of the reference one (SM). The strengthening techniques using GFRP sheets and steel bars increased the ultimate strength by about 46% and 16%, respectively, in comparison with the un-strengthened slab with an opening (SOM). Moreover, the RC slabs reinforced with higher reinforcement ratio (SOGM2 and SOGC2) exhibited a higher strength than those with the lower one (i.e., SOGM1 and SOGC1) under a similar loading.

Cyclic loading decreased the ultimate strength by about 5% in (SOGM1 and SOGC1). The test results show that this percentage of specimens reinforced by larger reinforcement ratio (1.77%) is about 11% (SOGM2, SOGC2). Thus, an increase in flexural reinforcement ratio and GFRP strengthening sheet layers can result in a higher drop in the ultimate strength due to the cyclic loading.

3.2 Load versus Deflection Relationships

Figure 5 shows load-deflection relationships for slabs. Figs. 5(a) and 5(b) present the deflection of the opening corner and the middle of the opening side of the slab, respectively. For cyclic loadings, the envelopes of the load-deflection curves are shown in these figures.

According to Fig. 5, it is obvious that the deflection at the middle of the opening side is more than that of the opening corner. The behavior of the slabs strengthened with GFRP sheets is more brittle than that of the others. Their load-deflection relationships drop suddenly after the failure, because of GFRP de-bonding. Slab SOSM (the slab with opening strengthened with extra steel bars) exhibits the most ductility among all strengthened slabs, because of using extra steel bars along the opening sides. The reference (SM) and control slab (SOM) exhibit the most and least ultimate strength among all slabs, respectively. The test results have also shown that the load-deflection relationship for the slab with opening strengthened with GFRP sheets (SOGM1) is similar to the slab without opening (SM). In comparison, the GFRP strengthened slab (GFRP) has a brittle behavior.

ACI code uses the same deflection control in the slabs with and without opening. One of the parameters investigated in this study is the deflection value of the slabs with and without opening. The deflection of flexural members is often controlled using the service loads. In this study, the service load is considered as 60% of the ultimate load of the reference slab (SM). At this load (0.6 × 260 = 156 kN), the effect of opening and strengthening of the slab on deflection is studied. At the load 156 kN, the deflections of the slabs with opening SOGM1 and SOSM are 1.18 and 1.29 times the slab SM (the reference slab without opening), respectively. Therefore, the strengthened slabs with an opening may exceed the deflection requirements applied by different codes for the reinforced concrete slabs.

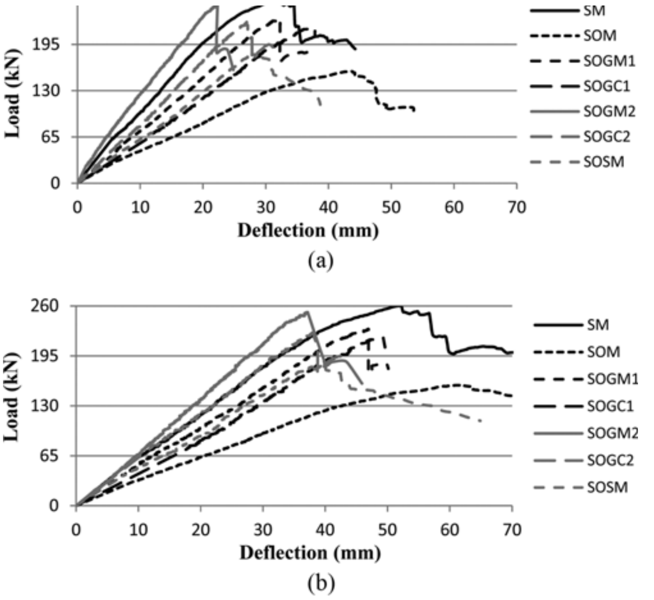


Fig. 5. Load-deflection Relationships for All Slabs: (a) Opening Corner, (b) Middle of Opening Side

The deflections at service load for the slabs SOGM2 and SOGC2 are 69.4% and 72.4% of the slabs SOGM1 and SOGC1, respectively. Therefore, larger flexural reinforcement ratio (1.77%) resulted in smaller deflection values.

Cyclic loading increases the deflection at service load by 18.4% for the slabs with the flexural reinforcement ratio of 0.87% (for SOGM1 and SOGC1). The test results show that for the specimens with the flexural reinforcement ratio of 1.77% (for SOGM2 and SOGC2), the deflection increases by 23.5%.

Stiffness is defined as a load to deflection ratio. The average stiffness at ultimate load can be assumed as the ratio of the ultimate load to the deflection at this point (Fig. 5). The un-strengthened slab with an opening (SOM) exhibits the lowest stiffness among all specimens. Strengthening such slab may enhance the stiffness. The test results showed that using GFRP sheets (SOGM1) could lead to a higher stiffness than that of extra steel bars (SOSM). The highest stiffness among all strengthened slabs is for slab SOGM1 (GFRP strengthened), which is about twice the control one (SOM). This value for slab SOSM (strengthened by extra steel bars) is about 1.8. The stiffness for slab SM (without opening) is 2.1 times the slab with an opening (SOM). Thus, the stiffness was not restored completely by GFRP strengthening technique. The results also showed that

Table 4. Slabs Stiffness

Slab	$Su\left(\frac{kN}{mm}\right)$	
	Opening corner	Middle of opening side
SM	8.0	5.0
SOM	3.6	2.5
SOGM1	7.1	4.9
SOGC1	5.8	4.4
SOGM2	11.3	6.8
SOGC2	8.4	5.9
SOSM	6.3	4.6

Note: S_u = ftiffness

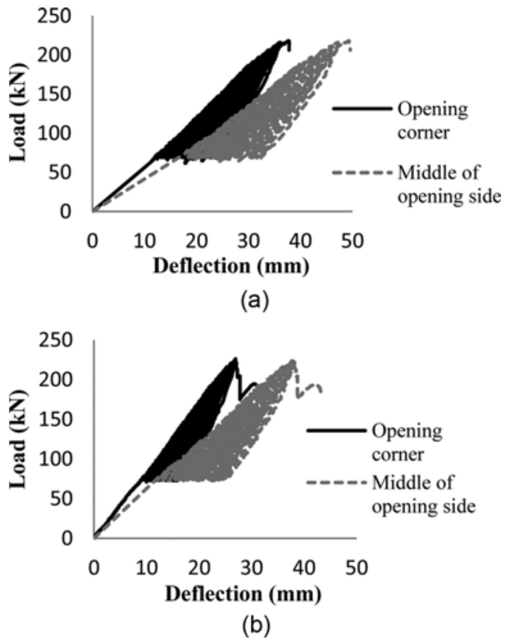


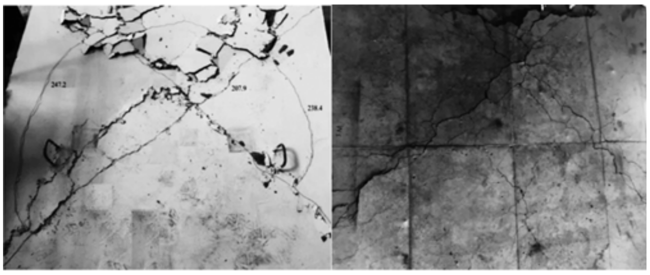
Fig. 6. Load-deflection Relationships for the Slabs subjected to Cyclic Loading: (a) Slab SOGC1, (b) Slab SOGC2

by an increase in the reinforcement ratio (1.77%) the stiffness would become about 1.45 times of those reinforced by less reinforcement ratio. The stiffness of slabs under monotonic loading is about 1.2 times of slabs under cyclic loading. Table 4 shows the stiffness of the slabs.

The envelope of load-deflection curves for the slabs subjected to cyclic loading basically traced the monotonic ones. However, all cyclic load-deflection curves are under the monotonic curve. Fig. 6 shows load-deflection relationships for the slabs subjected to cyclic loading.

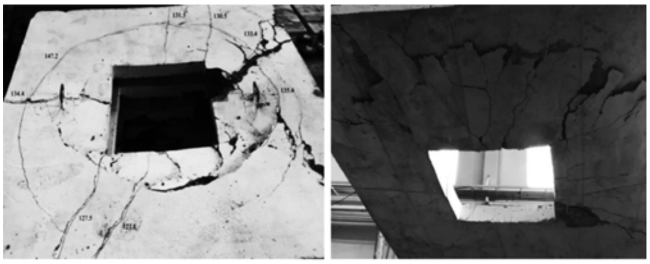
3.3 Failure Modes and Cracking Patterns

According to the test results (Table 3), three failure modes were observed; i.e., a flexural failure, a flexural-punching shear failure, and a GFRP debonding-punching shear failure. The cracking initiation and propagation concur with the results observed by Enochsson e*t al.* (2007).



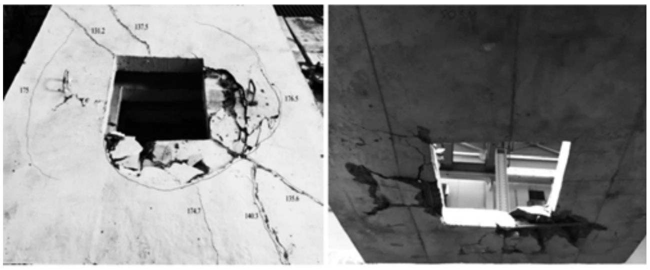
(a) (b)

Fig. 7. The Failure Mode and Cracking Pattern for Slab SM: (a) Compression Side, (b) Tension Side



(a) (b)

Fig. 8. The Failure Mode and Cracking Pattern for Slab SOM: (a) Compression Side, (b) Tension Side



(a) (b)

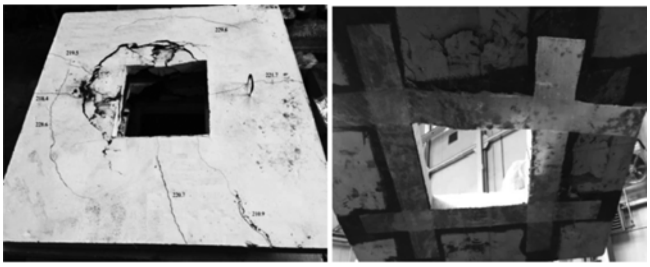
Fig. 9. The Failure Mode and Cracking Pattern for the Slab SOSM: (a) Compression Side, (b) Tension Side

3.3.1 Flexural Failure

This failure mode was observed only in slab SM (without opening). It is characterized by yielding of tensile steel reinforcement followed by concrete crushing on the compression side of the slab. The failure mode and cracking pattern are shown in Fig. 7.

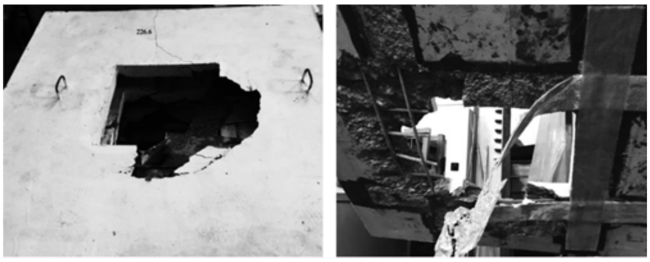
3.3.2 Flexural-punching Shear Failure

This failure mode occurred in the slabs with an opening not strengthened by GFRP sheets (Fig. 8). In slab SOM (un-strengthened with the opening), the cracks propagated from the opening sides to the slab edges. A circular crack appeared before the breakdown. At the end, the punching failure occurred around the opening and the specimen collapsed at 157 kN. Fig. 8 shows



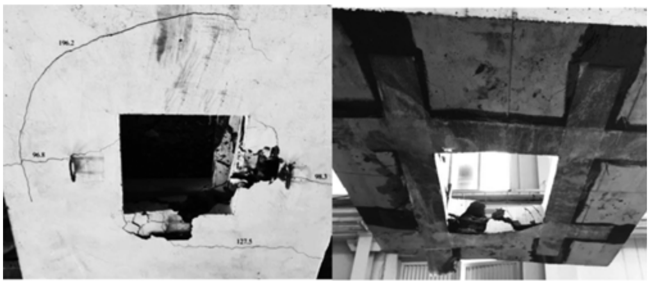
(a) (b)

Fig. 10. The Failure Mode and Cracking Pattern for Slab SOGM1: (a) Compression Side, (b) Tension Side



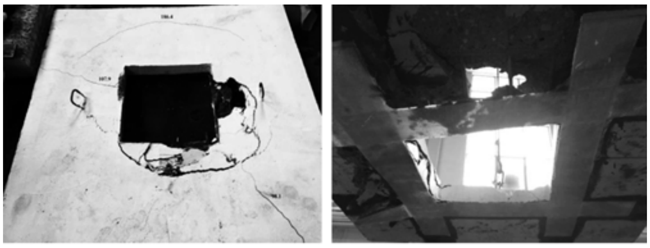
(a) (b)

Fig. 12. The Failure Mode and Cracking Pattern for Slab SOGM2: (a) Compression Side, (b) Tension Side



(a) (b)

Fig. 11. The Failure Mode and Cracking Pattern for Slab SOGC1: (a) Compression Side, (b) Tension Side



(a) (b)

Fig. 13. The Failure Mode and Cracking Pattern for Slab SOGC2: (a) Compression Side, (b) Tension Side

the failure mode and cracking pattern.

In the slab SOSM (with opening strengthened by steel bars), the cracks propagated similarly to the slab SOM. A circular crack was appeared just before the breakdown. The failure mode and cracking pattern are shown in Fig. 9.

3.3.3 GFRP Debonding-punching Shear Failure

This failure mode was observed in the GFRP strengthened slabs with the opening. The failure occurs suddenly with the punching shear failure followed by a loud noise of FRP-debonding.

Figure 10 shows the failure mode and cracking pattern of the slab SOGM1 (GFRP-strengthened with opening subjected to monotonic loading).

The failure mode and cracking pattern for the slab SOGC1 (GFRP-strengthened with opening subjected to cyclic loading) are shown in Fig. 11.

Figures 12 and 13 show the failure mode and cracking pattern of slab SOGM2 (14 mm steel bars reinforced slab with opening strengthened by GFRP subjected to monotonic loading) and slab SOGC2 (14 mm steel bars reinforced slab with opening strengthened by GFRP subjected to cyclic loading), respectively.

The GFRP strengthened RC slabs with opening have a unique debonding process. The debonding begins on the GFRP sheet/concrete interface at one end of the GFRP sheet and then propagates along the opening side of the slab. For the slabs subjected to cyclic loading, the debonding initiation occurred at the earlier load level, because of repeated loading that led to degradations in the GFRP-adhesive interface stiffness.

4. Conclusions

The behavior of two-way RC slab with and without opening, strengthening effectiveness, loading type, reinforcement ratio, and a number of GFRP layers were investigated in this experimental study. According to load-deflection relationships, cracking patterns, and failure modes of specimens, the following results are drawn:

1. Introducing a central opening in an existing slab could decrease the ultimate strength by about 40%. Using GFRP sheets for strengthening RC slabs with the opening is more effective than using extra steel bars (proposed by ACI 318-14, 2014) in increasing the ultimate load-carrying capacity. The test results show that the specimen with opening strengthened by GFRP sheets could exhibit 88% of the ultimate strength of the reference slab (the slab without opening). However, using extra steel bars shows only 70% of the ultimate load-carrying capacity of the reference slab. Moreover, the ultimate strength was not enhanced considerably in the slabs with larger flexural reinforcement ratio. It is worth mentioning that ACI 318-14 (2014) provisions for strengthening RC slabs with an opening by extra steel bars may not restore the ultimate load-carrying capacity of the slab to the value of the slab without opening.
2. At the service load, the deflections of the slabs with opening

strengthened with GFRP sheets and extra steel bars are 1.18 and 1.29 times the slab without opening, respectively. ACI 318-14 (2014) provisions use the same deflection control for the slabs with and without opening. Therefore, the slabs strengthened with an opening may exceed the deflection requirements applied by different codes for the reinforced concrete slabs. Moreover, increasing the reinforcement ratio of the slabs resulted in decreasing the deflection value at the service load. The test results have also shown that using GFRP strengthening method for the slab with an opening could lead to a load-deflection relationship like the slab without opening.

3. Cyclic loading decreased the maximum load-carrying capacity of the slabs with smaller reinforcement ratio by about 5%. The test results show that the slabs with larger flexural reinforcement ratios exhibit further decreasing in the ultimate strength caused by cyclic loading. In these slabs, cyclic loading could decrease the ultimate strength by about 11%.

References

Afefy, H. M. and Fawzy, T. M. (2013). “Strengthening of RC one-way slabs including cut-out using different techniques.” *Engineering Structures*, Vol. 57, pp. 23-36, DOI: 10.1016/j.engstruct. 2013.09.013.

ACI (2014). *Building code requirements for structural concrete and commentary*, American Concrete Institute, Farmington Hills, MI, USA.

ACI 440 (2008). *Guide for the design and construction of externally bonded FRP system for strengthening concrete structures*, American Concrete Institute, Farmington Hills, MI, USA.

ASTM A370-17a (2008). *Standard test methods and definitions for mechanical testing of steel products,* American Society for Testing and Materials.

Arduini, M., Nanni, A., and Romagnolo, M. (2004). “Performance of one-way reinforced concrete slabs with externally bonded fiber-reinforced polymer strengthening.” *ACI Structural Journal*, Vol. 101, No. 2, pp. 193-201, DOI: 10.14359/13016.

Casadei, P., Nanni, A., and Ibell, T. (2004). *Experiments on two-way RC slabs with openings strengthened with CFRP laminates*, Center for Infrastructure and Engineering Studies, Missouri University of Science and Technology, Rolla, Missouri, USA.

Ebead, U. and Marzouk, H. (2004). “Fiber-reinforced polymer strengthening of two-way slabs.” *ACI Structural Journal*, Vol. 101, No. 5, 650-659, DOI: 10.14359/13387.

Enochsson, O., Lundqvist, J., Täljsten, B., Rusinowski, P., and Olofsson, T. (2007). “CFRP strengthened openings in two-way concrete slabs – an experimental and numerical study.” *Construction and Building Materials*, Vol. 21. No. 4, pp. 810-826, DOI: 10.1016/j.conbuildmat. 2006.06.009.

Kim, S. J. and Smith S. T. (2009). “Strengthening of RC slabs with large penetrations using anchored FRP composites.” *The Second Official International Conference of International Institute for FRP in Construction for Asia-Pacific Region,* Seoul, Korea.

Limam, O., Nguyen, V. and Foret, G. (2005). “Numerical and experimental analysis of two-way slabs strengthened with CFRP strips.” *Engineering Structures Journal*, Vol. 27, No. 6, pp. 841-845, DOI: 10.1016/ j.engstruct.2005.01.007.

Mosallam, A. S. and Mosalam, K. M. (2003). “Strengthening of two-way concrete slabs with FRP composite laminates.” *Construction and Building Materials*, Vol. 17, No. 1, pp. 43-54, DOI: 10.1016/ s0950-0618(02)00092-2.

Robertson, I. and Johnson, G. (2004). “Repair of slab-column connections using epoxy and carbon fiber reinforced polymer.” *Journal of Composites for Construction*, Vol. 8, No. 5, pp. 376-383, DOI: 10.1061/(ASCE)1090-0268(2004)8:5(376).

Seim, W., Hörman, M., Karbhari, V., and Seible, F. (2001). “External FRP post-strengthening of scaled concrete slabs.” *Journal of Composites for Construction*, Vol. 5, No. 2, pp. 67-75, DOI: 10.1061/(ASCE)1090-0268(2001)5:2(67).

Smith, S. T. and Kim S. J. (2009). “Strengthening of one-way spanning RC slabs with cutouts using FRP composites.” *Construction and Building Materials*, Vol. 23, No. 4, pp. 1578-1590, DOI: 10.1016/ j.conbuildmat.2008.06.005.