STRENGTHENING OF SELF-COMPACTED CONCRETE TWO WAY SLABS WITH OPENING USING NEAR SURFACE MOUNTED (NSM) FIBER REINFORCED POLYMERS (FRP) TECHNIQUE

Azhar G. Hamad and Anis A. Mohamad Ali
Civil Engineering Department, Engineering College, University of Basrah, Iraq
Email address: co.azhar@yahoo.com

Abstract:
The effectiveness of near-surface-mounted carbon-fiber-reinforced polymers on strengthening of self-compacted concrete two-way slabs with opening was investigated experimentally. The experimental work included testing eighteen specimen two-way slabs with an opening, which included 6 control specimens and 12 strengthened with CFRP strips and tested under four-line load around the opening. The dimensions of the slab specimens are (1000 × 1000) mm, (100) mm depth. The reinforced concrete slabs containing a single concentric opening with 3 different skew angles (0°, 30° and 45°) strengthened by CFRP strips. Strengthening effectiveness was investigated on slabs using near-surface-mounted carbon-fiber-reinforced polymer strips with inclined and combined configurations. The results showed, firstly, that the load-carrying capacities of the self-compacted concrete slabs with openings have been decreasing with skew angle increasing and secondly that using near-surface-mounted carbon-fiber-reinforced polymers increases the ultimate strength of two way slab self-compacted concrete slabs by (1%–32%) for both strengthening configurations, with the combined configurations performing better. Also, the cracking load and stiffness increased, while deflection and toughness decreased.

Keywords: near-surface-mounted carbon-fiber-reinforced polymers, self-compacted concrete, strengthening, two-way slabs with an opening.

1. INTRODUCTION

During the life span of bridges, buildings, and other concrete structures, concrete members need to be renovated due to many cases. In these cases it may become necessary to introduce sectional openings in existing slabs of buildings and industrial
facilities. In some instances the requirement for an opening was one of the most general issues occurring in the structural engineering when dealing with R.C. slab, placing staircases, new elevators, fire sprinkler pipes, plumbing systems, additional skylights, AC pipes, ventilation and heat (HV) ducts, and general services (electricity, wiring ducts and telephones) [1].

Strengthening using the FRP techniques, such as externally bonded FRP or near-surface mounted (NSM), has become an attractive method nowadays by improving RC structures capacities. Compared to traditional strengthen techniques, strengthen using FRP materials has many advantages, such as lower maintenance cost, corrosion resistance, high strength-to-weight ratio, and easy and fast installation. Many near-surface-mounted fiber reinforced polymer (NSM-FRP) shapes have been produced, including square, round, oval, and rectangular. Round bars are easily available and have an advantage in pre-stressing anchoring operations, while square bars need large grooves. Narrow strips have a maximum surface area to cross-sectional area, which minimizes the probability of debonding failure. The use of these shapes depends on the state of affairs of cover depth, and availability of these shapes [2-5]. The effectiveness of the NSM-FRP technique depends on many parameters, which include bond strength, number, orientation and type of FRP, groove dimensions, size, and location of NSM application [6-10].

Several studies have been conducted on two-way with an opening strengthened slabs using different strengthening techniques [11-15]. Vasques and Karbhari [11] studied the effectiveness of externally bonded FRP strips for strengthening slabs with only one type
of opening shape. An average gain of original load carrying capacity of slabs weakened by cutouts when using FRP strips. Al-Fatlawi and Abed [15] presented a study of the performance of the two-way RC slabs with one central opening and two openings having area equal to the area of one opening. Also, studying the effect of strengthening by using CFRP sheets bonded to tension face, and the effect of the provided length of CFRP sheets.

The bond between the concrete and the NSM-FRP reinforcement is responsible for the stress transfer between the materials and is a critical factor in the efficiency of this technique. Bond strength depends on bond length, groove dimensions, groove filler, surface roughness of grooves, bar diameter, and surface configuration of bars [16-17]. Debonding loads increase by increasing bond length, compressive strength of concrete, and groove width [18-19]. Sharaky et al. [20] found that bond length, bar diameter, and adhesive properties are the main parameters affecting bond strength and load capacity.

Groove dimensions are a secondary parameter, since they depend on the adhesive properties, but groove shape has no effect on the failure mode or load capacity.

Self-compacted concrete (SCC), a flowable and highly durable concrete, is one of the recent advances in concrete technology with increasing application. This type of concrete requires no vibration, as it is compacted by its own weight. SCC was first developed and implemented in 1988 in Japan to obtain durable concrete structures, due to a lack of skilled labor for concrete compaction [21]. Remarkable, filling, workability and passing ability make SCC an optimal material to restore damaged concrete elements. Recently, it
has been used in jacketing applications for the repair and/or strengthening of intact and damaged RC members [22-24].

It is evident from literature that virtually the studies available on behavior of self compacted RC two way slabs with opening strengthened with NSM CFRP reinforcement are still very limited. Therefore, more resources is needed experimentally to understand the behavior of strengthened two way RC slabs using NSM-CFRP.

Hence, the current research is to investigate the influence of NSM-CFRP techniques on the behavior of two-way SCC slabs. The research consists of two main points: strengthening work and the effect of the skew angle of the opening. The program include eighteen specimens two-way slabs with an opening, which include 6 control specimens and 12 specimens strengthened with CFRP strips. The reinforced concrete slabs containing a single concentric opening with 3 different skew of angles (0°, 30° and 45°) strengthened by NSM-CFRP strips. The strengthening work using NSM-CFRP strips was done with two configurations (inclined and combined) to find the best economical strengthening orientation.

2. EXPERIMENTAL PROGRAM

2.1. Test specimens

Eighteen self-compacted concrete two way slabs (1000x1000x100 mm) with central opening (280x280 mm) were cast and divided into three major groups; six two-way slabs with an opening with skew angle 0°, the 2nd group also of six slabs with an opening of skew angle 30° and finally six slabs with an opening of skew angle 45°. The two-way slabs were reinforced with 7ϕ10mm in both
directions. Table 1 summarizes the details of the test specimens and the different test parameters and Figure 1 displays the reinforcement details of the test specimens.

Table 1: Test specimens' designations and test parameters

| Slab Dimensions | Opening Skew Angle | Slab Designation | Number of Slabs | FRP Configuration |
|-----------------|-------------------|-----------------|----------------|------------------|
| Control Slabs   |                   |                 |                |                  |
| Two-Way         | 0°                 | C-0             | 2              | -                |
| 1000x1000x100 mm|                   |                 |                |                  |
| 30°             |                   | C-30            | 2              | -                |
| 45°             |                   | C-45            | 2              | -                |
| S-W-0-I         | 2                 | Inclined        |                |                  |
| 0°              |                   | S-W-0-C         | 2              | Combined         |
| Strengthen Slabs|                   |                 |                |                  |
| Two-Way         | 30°                | S-W-30-I        | 2              | Inclined         |
| 1000x1000x100 mm|                   | S-W-30-C        | 2              | Combined         |
|                 |                   | S-W-45-I        | 2              | Inclined         |
| 45°             |                   | S-W-45-C        | 2              | Combined         |

1° C = control, S = strengthened, I = inclined strips configuration, 2nd C = combined strips configuration
Figure 1: Layout and detailing of slabs specimens
2.2. Material properties

Concrete: The SCC mix was prepared using Type I ordinary Portland cement, crushed coarse aggregate, fine aggregate, water, and a super-plasticizer. The crushed coarse aggregates had a maximum size of 12.5 mm, and the fine aggregate was a mixture of crushed fine aggregate and silica sands (60% fine limestone and 40% silica sand). All those materials were tested according to ASTM specifications C128 & C128. The specific gravity and absorption were 2.63% and 1.5% for coarse limestone aggregates, respectively. The specific gravity, absorption, and fineness modulus for the fine aggregate were 2.46, 1.5%, and 2.7, respectively. A 0.4 water-to-cement ratio was used in the SCC mix design. Many trial mixes were made to obtain the best proportion, depending on the properties of the materials used. The dosage of super-plasticizer and retarding admixture were adjusted in each mix to achieve the workability requirements for SCC without segregation. The quantities of cement, water, coarse aggregate, fine aggregate, and silica sand were 450, 180, 743, 510, and 340 kg/m$^3$, respectively. Available super-plasticizer (Structuro 520) was used at a 0.85% cement ratio to improve the concrete workability.

Reinforcing steel: All slabs were reinforced with 10 mm diameter steel bars. The yield strength, ultimate strength, and elongation at failure of the steel bars were 432 MPa, 660 MPa, and 10%, respectively.

NSM-CFRP: SIKA brand NSM-CFRP strips (Sika S1525) were used in the present study for strengthening and repair of the self-compacted RC slabs. Table 2
lists the physical, geometrical, and mechanical properties of those NSM-CFRP strips as provided by the manufacturer.

*Sikadur epoxy paste adhesive:* Sikadur adhesive epoxy (Sikadur 30LP) was used to bond NSM-CFRP strips to the self-compacted RC slabs. Sikadur is composed of two components: epoxy (Component A) and hardener (Component B). Sikadur requires 7 days of curing at room temperature. The Sikadur epoxy has a mean tensile strength of 3100 N/mm² and a tensile modulus of 165 N/mm².

Table 2: Properties of CFRP strips

| Fiber type                  | High strength carbon fibers |
|-----------------------------|-----------------------------|
| Fiber orientation          | 0                           |
| Fiber density               | 1.6 g/cm³                   |
| Strip width                 | 15 mm                       |
| Strip thickness             | 2.5 mm                      |
| Cross sectional area        | 37.5 mm²                    |
| Mean tensile strength       | 3100 N/mm²                  |
| Tensile E-modulus           | 165 / mm²                   |
| Strain at break             | > 1.7 % (nominal)           |

2.3. Mixing and casting

Concrete mixing was achieved by using a tilting drum mixer machine of 0.15 m³ capacity. Prior to slab casting, a slump-flow test, V-funnel test, and L-Box test were performed on the fresh concrete to determine the properties of SCC, such as its flow ability and passing ability, according to relevant specifications [25]. The slump flow, V-funnel time, and L-Box results for the SCC mixture in this study were 685 mm, 9s, and 0.9, respectively, meeting the requirement for SCC, per
EFNARC [25]. Then, the wooden molds were oiled and the steel cages placed inside. Next, the concrete was poured and self compacted, and the slabs’ top surface finished smooth via trowel. After 24 hours, the slabs were demolded and covered with wet burlap for 28 days, then transferred to an open environment awaiting for the strengthening and repair process.

2.4. Strengthening process

The procedure for strengthening two-way RC slab specimens with NSM CFRP strips is detailed below and shown in Figures 2&3. Slabs were strengthened with NSM-CFRP strips in two configurations: inclined and combined. Grooves on the slab surface were located using an adhesive tape and a pencil. Then, the NSM-CFRP strips were cut to the needed lengths using a special FRP cutter. The 8 mm width and 20 mm depth grooves were made by a saw. To finalize the grooves, a manual hammer and chisel were used. The grooves were then cleaned with water under pressure. To ensure a dry surface before bonding the strips to the concrete, the slabs were air-dried in the laboratory environment before the CFRP strips were bonded. Next, the Sikadur epoxy was mixed according to the instructions; the ratio between epoxy (Component A) and hardener (Component B) is 3:1. After that, a layer of epoxy was applied to the grooves. The CFRP strip was then pressed into the groove and a second layer of adhesive was applied on top of the CFRP. The surface was then cleaned and the epoxy was allowed to cure for 7 days to achieve target strength. Table 1 shows the test specimens and the different test parameters.
2.5. Test setup

The test was performed using a steel frame especially fabricated to support the slab dimensions of this research. Figure 4 displays details of the frame model.

All test slab specimens were subjected to four line-static load system around the opening to failure using the hydraulic testing machine of 2000 kN capacity available at the structural laboratory, JUST. A four linear variable differential transducers (LVDT) located at the corners of the opening beneath the slab specimens were used to measure the deformation of the slabs. The load was
gradually applied and the testing data (the load and displacements values) were automatically recorded using a data acquisition system.

3. TEST RESULTS AND DISCUSSION

The results have been analyzed based on cracking behavior, vertical deflection, and failure mode, which included the first cracking load and ultimate load. The experimental results are presented and compared. The results showed that the external strengthening of R.C. slabs by NSM-CFRP strips gave a better enhancement in comparison with control slab in these groups.

3.1. First Cracking Loads

Table (3) presents the first cracking load obtained from the experimental work. Generally, the first crack load in slabs with opening and without strengthening was less than that of strengthened slabs. Slab specimens strengthened with combined configuration showed different values for the first cracking load.
3.2. Ultimate Loads and Failure Modes

Table (3) shows the ultimate load and the failure mode of slabs containing openings of different skew angles strengthened using NSM-CFRP strips. It was observed that the presence of an opening in the slab causes a decrease in ultimate load with increasing in the opening skew angle. The NSM-CFRP strips strengthening method introduced a slight improvement in the value of the ultimate load when compared to the slab without strengthening in same group and the major reason is the discontinuity between the ends of the strips.

3.3. Cracking Patterns

The flexural cracks in slabs with an opening (C-0, C-30 and C-45) appear in corners of the opening due to no steel-skew reinforcement found, those cracks propagate towards the corners of the slabs. Some of those cracks sliced through the plane of the slab. This can be interpreted as a form of punching shear behavior. All slabs failed similarly in flexure, following concrete crushing. For the strengthened slab with inclined configuration S-W-0-I, S-W-30-I and S-W-45-I slabs, flexural cracks initiated at the corner of the opening, due to high CFRP strips near to the tip of the cracks path which slid around the strips area and some of this cracks sliced through the plane of the slab and this form of cracks can be interpreted as a form of punching shear behavior. With further application of the load, debonding-type of failure wasn’t identified because the cracks propagated towards the weak area of the slab which is without strips. With further application of the load, the cracks propagated rapidly towards the high tension zone until failure by crushing of compression concrete. Slabs strengthened with the
combined configuration, flexural cracks initiated at the corner of the opening, due to high CFRP strips near to the tip the cracks path which slid into the discontinuity areas between the ends of the strips and some of those cracks sliced through the plane of the slab and this form of cracks can be interpreted as a form of punching shear behavior. With further application of the load, debonding-type of failure for the strips identified because of the formation of horizontal cracks in concrete cover at the termination points of the NSM CFRP strips. Figure 5 and Figure 6 shows the mode of failure for the slabs.

3.4. Deflections and Stiffness

The measurement of deflections for all slabs have been taken till failure. A four linear variable differential transducers (LVDT) located at the corners of the opening from the bottom of the slab specimens were used to measure the deformation of the slabs. Figure 7 to Figure 9 shows a comparison of load deflections curves of all the reinforced concrete slabs in this study. It was observed that the presence of opening in the slab causes a decrease in stiffness and deflection with increasing in skew angle of opening. The CFRP strips presence improved the behavior of slabs with strengthening when compared to the slab without strengthening in same group by increased the stiffness and decreasing the deflection.
Figure 5: Failure modes for slabs with different skew angle of the opening (0°, 30° and 45°) with: (a) no CFRP Strips (b) three CFRP strips inclined configuration (c) CFRP strips with combined configuration
Figure 6: Failure modes for slabs (a) Cracks slid through the plane of the slab
(b) Debonding-type failure at the termination points of the CFRP strips
**Table 3:** First cracking loads of the slabs

| Specimen   | First cracking load (kN) |
|------------|--------------------------|
| C-0        | 40                       |
| C-30       | 33                       |
| C-45       | 33                       |
| S-W-0-I    | 41                       |
| S-W-0-C    | 60                       |
| S-W-30-I   | 40                       |
| S-W-30-C   | 40                       |
| S-W-45-I   | 42                       |
| S-W-45-C   | 45                       |
### Table 4: Ultimate capacities and deflection characteristics for preloaded two-way slabs

| Slab Designation | Ultimate load, Pu, kN | Ultimate deflection, δu, mm | Stiffness, K, kN/mm | Toughness, (J) | Failure mode |
|------------------|-----------------------|-------------------------------|---------------------|----------------|--------------|
| C-0A             | 120                   | 21                            | 28.5                | 2097           | Flexural failure |
| C-0B             |                       |                               |                     |                |              |
| S-W-0-IA         |                       |                               |                     |                |              |
| S-W-0-IB         |                       |                               |                     |                |              |
| S-W-0-CA         |                       |                               |                     |                |              |
| S-W-0-CB         |                       |                               |                     |                |              |
| C-30A            | 98                    | 16                            | 17                  | 1152           | Flexural failure |
| C-30B            |                       |                               |                     |                |              |
| S-W-30-IA        |                       |                               |                     |                |              |
| S-W-30-IB        |                       |                               |                     |                |              |
| S-W-30-CA        |                       |                               |                     |                |              |
| S-W-30-CB        |                       |                               |                     |                |              |
| C-45A            | 88                    | 16                            | 18                  | 976            | Flexural failure |
| C-45B            |                       |                               |                     |                |              |
| S-W-45-IA        |                       |                               |                     |                |              |
| S-W-45-IB        |                       |                               |                     |                |              |
| S-W-45-CA        |                       |                               |                     |                |              |
| S-W-45-CB        |                       |                               |                     |                |              |
Figure 7: Load-deflection curves for control (C-0, C-30 and C-45)

Figure 8: Load-deflection curves for control (C-0, C-30 and C-45) and strengthen (S-W-0-I, S-W-30-I and S-W-45-I) slabs.
Figure 9: Load-deflection curves for control (C-0, C-30 and C-45) and strengthen (S-W-0-C, S-W-30-C and S-W-45-C) slabs.
4. CONCLUSIONS

The following point illustrate the conclusions obtained from the experimental study.

1. The presence of opening in the slab causes a decrease in ultimate load, stiffness and deflection with increasing in skew angle of opening.

2. The discontinuity between the ends of the NSM-CFRP strips cause a slightly improvement in the value of the ultimate load when compared to the slab without strengthening in same group.

3. Delaying the appearance of crack and reducing the crack width of the reinforced concrete two way slab with openings when strengthened with CFRP strips.

4. The stiffness of the strengthened R.C. two way slabs with openings increased while deflection and toughness decreased.
References

[1] Casadei P., Ibell T., and Nanni A. (2006) Experimental Results of One-Way Slabs with Openings Strengthened with CFRP Laminates, Proceedings of the Sixth International Symposium on Fiber Reinforced Polymer Reinforcement of Reinforced Concrete Structures, Singapore, July 8-10, Vol. 2, PP. 1097-1106.

[2] De Lorenzis L and Nanni A (2002) Bond between nearsurface mounted fiber-reinforced polymer rods and concrete in structural strengthening. ACI Structural Journal 99: 123–132.

[3] De Lorenzis L and Teng J (2007) Near-surface mounted FRP reinforcement: an emerging technique for strengthening structures. Composites Part B: Engineering 38(2): 119–143.

[4] El-Hacha R and Rizkalla SH (2004) Near-surface-mounted fiber-reinforced polymer reinforcements for flexural strengthening of concrete structures. ACI Structural Journal 101: 717–726.

[5] El-Hacha R, Silva FN, Melo GS, et al. (2004) Effectiveness of near-surface mounted FRP reinforcement for flexural strengthening of reinforced concrete beams. In: 4th international conference on advanced composite materials in bridges and structures, Calgary, AB, Canada, 20–23 July.

[6] Blaschko M (2003) Bond behaviour of CFRP strips glued into slits. In: Sixth international symposium on FRP reinforcement for concrete structures (FRPRCS-6), 8–10 July. Singapore: World Scientific Publishing Co Pvt Ltd., pp. 205–214.

[7] De Lorenzis L, Nanni A and Tegola A (2000) Strengthening of reinforced concrete structures with near-surface mounted FRP rods. In: International meeting on composite materials, PLAST 2000, proceedings, advancing with composites, Milan, 9–11 May.

[8] Hassan T and Rizkalla S (2004) Bond mechanism of nearsurface-mounted fiber-reinforced polymer bars for flexural strengthening of concrete structures. ACI Structural Journal 101(6): 830–839.

[9] Parretti R and Nanni A (2004) Strengthening of RC members using near-surface mounted FRP composites: design overview. Advances in Structural Engineering 7(6): 469–483.
[10] Sharaky I, Torres L, Baena M, et al. (2013) An experimental study of different factors affecting the bond of NSM FRP bars in concrete. Composite Structures 99: 350–365.

[11] Vasques, A., and V. M. Karbhari. (2003) Fiber Reinforced Polymer Composite Strengthening of Concrete Slabs with Cutouts. ACI Structural Journal, V. 100, No. 5 (September–October): pp. 665–673.

[12] Enochsson, O., J. Lundqvist, B. Taljsten, P. Rusinowski, and T. Olofsson. (2007) CFRP Strengthened Openings in Two Way Concrete Slabs-An Experimental and Numerical Study, Journal of Construction Building Materials, V. 21, No. 4 (April): pp. 810–826.

[13] Muhammed N. J. (2012) Experimental Study of Self Compacting RC Slabs with Opening Strengthening with Carbon Fiber Laminated and Steel Fiber. Journal of Engineering and Development, Vol. 16, No.1, March, ISSN 1813-7822.

[14] Ye Ch( 2016) Strengthening of Slab With Openings Located in The Shear Zone with CFRP Sheets and Anchors, Thesis of The Degree of B. Eng (Hons.) Civil Engineering, Faculty of Civil Engineering and Earth Resources, University Malaysia Pahang.

[15] Al-fatlawi A. S. and Abed H. A. (2015) CFRP Strengthening of Concrete Slabs with and without Openings, International Journal of Science and Technology, Vol. 4.

[16] Galati D and De Lorenzis L (2009) Effect of construction details on the bond performance of NSM FRP bars in concrete. Advances in Structural Engineering 12(5): 683–700.

[17] Khshain N, Al-Mahaidi R and Abdouka K (2015) Bond behaviour between NSM CFRP strips and concrete substrate using single-lap shear testing with epoxy adhesive. Composite Structures 132: 205–214.

[18] Elgabbas F, El-Ghandour A, Abdelrahman A, et al. (2010) Different CFRP strengthening techniques for prestressed hollow core concrete slabs: experimental study and analytical investigation. Composite Structures 92(2): 401–411.
[19] Tanarslan H (2011) The effects of NSM CFRP reinforcements for improving the shear capacity of RC beams. Construction and Building Materials 25(5): 2663–2673.

[20] Sharaky I, Torres L, Comas J, et al. (2014) Flexural response of reinforced concrete (RC) beams strengthened with near surface mounted (NSM) fiber reinforced polymer (FRP) bars. Composite Structures 109: 8–22.

[21] Okamura H and Ouchi M (2003) Self-compacting concrete. Journal of Advanced Concrete Technology 1(1): 5–15.

[22] Chalioris CE and Pourzitidis CN (2012) Self-compacting concrete jacketing—tests and analysis. In: Proceedings of the AASRI procedia, conference on modeling, identification and control (MIC ’12), Hong Kong, 2012, paper no. 227. Elsevier.

[23] Yin X, Zhai S and Gong T (2012) Application of selfcompacting concrete in strengthening of existing reinforced concrete column. Advanced Materials Research 476–478: 1722–1725.

[25] EFNARC (2005) Specifications and Guidelines for Self-compacting Concrete. Surrey: Association House, pp. 1–32.