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Research Paper

Experimental Investigation of Two-Way Concrete Slabs Reinforced by Perforated Steel Plates Under Concentrated Load

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This research experimentally investigates the effect of using the perforated steel plate instead of steel bars as a reinforcing system in two-way concrete slabs. The study consists of casting four slabs using self-compacting concrete. Three slabs are reinforced by a perforated steel plate and one slab is reinforced by traditional bar reinforcement. The amount of steel in both types of reinforcement is equal. The slabs are tested under a monotonic concentrated load at their middle point. The results show a significant enhancement in behavior. The ultimate load increased about 43% to 76%, depending on the size of the openings. Moreover, the final crack width in all slabs reinforced by a perforated steel plate was smaller than in the slab reinforced by a traditional steel bar. The results of this study may be used in future research to introduce a method that will lead to an improvement in the overall behavior of two-way concrete slabs.

Key words: two-way slabs; concentrated load; self-compacting concrete; perforated plate; circle openings.

1. Introduction

Cost, time and specifications are the main aims for designers. Researchers try to find the optimal way to satisfy these objectives. This research tries to contribute and introduce a method for reinforcing two-way slabs by a perforated steel plate. It is clear that using perforated steel plate instead of traditional steel bars will reduce the effort and time of checking the reinforcement distribution process and the required distance between them as this is determined earlier. However, the main issue is the validity of using such a technique and experimentally investigating whether it will improve the behavior of two-way slabs or not.

This method began with the successful use of the plate to strengthen two-way concrete slabs. Zhang *et al.* [1] used different sizes of external steel plates fixed to the bottom face of two-way concrete slabs by a suitable epoxy resin, while Ebead and Marzouk [2] modified the way of fixing the plates through the use of steel bolts in different arrangement patterns. Rasheed and Al-Azawi [3] proved that the effect of plate dimensions is greater than the effect of thickness. Additionally, they observed that debonding occurs in some cases. Metwally [4] used the Abaqus program and verified all the experimental work conducted by Rasheed and Al-Azawi. Elbakry and Allam [5] employed the previous two methods and then introduced a modified technique consisting of steel anchor bolts and epoxy resin.

This research presents a perforated steel plate embedded in a concrete slab in the tension zone as a suggested reinforcing method instead of classical reinforcement. The work comprises of casting four slabs using self-compacting concrete and testing them under concentrated load. The overall dimensions of the slabs are $1050 \times 1050 \times 60$ mm. Three slabs are reinforced by a perforated steel plate and one is reinforced by traditional bar reinforcements. All four specimens have the same amount of steel. The openings of the perforated steel plates are of circular shape, and three different sizes are investigated. Small size with 12×12 openings, and each opening of a diameter equal to 68 mm, medium size with 8×8 openings with each opening of a diameter equal to 102 mm, and large openings with 4×4 openings in which each opening has a diameter equal to 204 mm. The assessment is based on a comparison of slabs reinforced by perforated steel plates and a slab reinforced by traditional bar reinforcements. The comparison consists of the ultimate resistance load, load-deflection curve, first crack load, and crack pattern.

2. Methods and materials

All the materials employed to complete the experimental part of this research are mentioned in this section. Moreover, the methodology of the test is described.

2.1. Type of concrete

Self-compacting concrete is the most suitable type of concrete that should be used to provide factors that help with the successful completion of the proposed method. Cement, fine aggregate, coarse aggregate, mineral and chemical admixture are the ingredients that should be used to produce self-compacting concrete [6, 7]. The following points show more details related to the ingredients:

- Cement: ordinary cement is used for casting the specimens of slabs.
- Fine aggregate: well-graded fine aggregate with a particle size ranging from 4.75 mm to 0.15 mm.
- Coarse aggregate: the maximum size of coarse aggregate is equal to 14 mm.
- Mineral admixture: a silica fume is used as a mineral admixture to increase the cohesion of the mix and reduce segregation.
- Chemical admixture: chemical admixture is one of the essential materials that give high workability and improve the consistency of the mix; Glenium 54 is used in this study.

The proportion of the mentioned above ingredients should satisfy three significant properties: flowability, passing ability and stability. Many trial mixes were prepared to find a suitable ratio. Table 1 shows the weight and proportion ratios for the best trial mix obtained and used in the present study.

Table 1. The proportions of materials for the best trial mix.

Materials	Cement	Water	Sand	Gravel	Glenium 54	Silica fume
Weight [kg]	7.272	2.691	12.726	14.544	0.131	0.4
Ratio	1	0.35	1.75	2	0.018	0.05

The compressive strength of the concrete cube is 44.6 MPa.

2.2. Details of reinforcing specimens

As stated before, there are two types of reinforcing slabs: traditional bar reinforcements and perforated steel plate. The first specimen is reinforced by a minimum amount of required steel in the tension zone [8]. The diameter of the bar is 6 mm and the distance between two successive bars is 250 mm. The remaining three specimens are reinforced by a perforated steel plate, 1 mm in thickness, with three sizes of openings, as shown in Table 2.

Table 2. Details of the perforated steel plate openings.

Describe of openings	Diameter [mm]	Distance between the openings' edges [mm]
Small opening	68.0	15.4
Medium opening	102.0	23.0
Large opening	204.0	46

The plate openings should have smooth edges to prevent the point of stress concentration, as it is a starting point for failure. The fiber laser cutting machine type (XQL-1330) is used to achieve the required perforated steel plate, as shown in Fig. 1. It is a computerized control machine.

Fig. 1. Fiber laser cutting machine type (XQL-1330).

The plate dimensions are 1000×1000 mm, and they were used as a reinforcing element for the specimens. Figure 2 shows the perforated steel plate used in this study.

a) b) c)

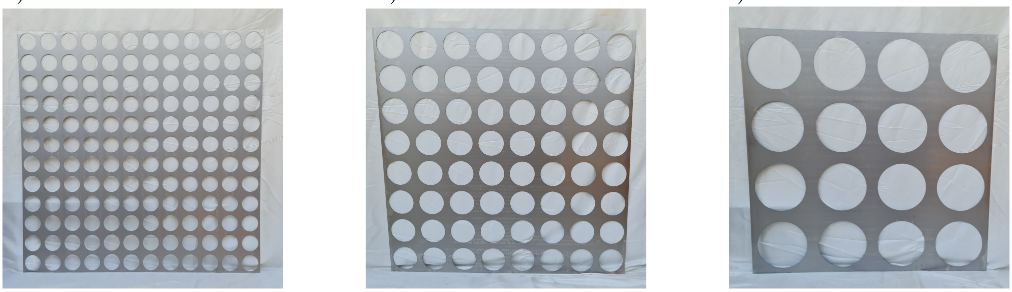

Fig. 2. Perforated steel plate: a) 12×12 openings, b) 8×8 openings, c) 4×4 openings.

The yield strength of the bar reinforcement is 590 MPa, and for the steel plate it is 280 MPa, so an equivalent amount between them was considered according to the following principle:

$$[V_s \times f_y]_{(\text{steel plate})} = [V_s \times f_y]_{(\text{bar reinforcement})}, \tag{2.1}$$

where V_s is the volume of steel and f_y is the yield strength of steel.

2.3. Supporting and loading condition

The specimens tested in the universal machine are subjected to a concentrated load of 15×15 cm at the top face of the slab at the middle point of the slabs [9]. The specimens are placed on rigid steel frames that provide simple supports. Figure 3 shows the final setup of the testing.

Fig. 3. Final setup of testing specimens.

3. Experimental results

This section is divided into three parts as clarified below.

3.1. Load deflection curve

In this study, three diameters of circular openings are considered: PSPC1-Co with a diameter of 68 mm and 12×12 openings, PSPC2-Co with a diameter of 102 mm and 8×8 openings, and the last one is PSPC3-Co, 204 mm in diameter with 4×4 openings. All three specimens are compared with a controlled specimen reinforced by a traditional deformed bar Re-Co, as shown in Fig. 4.

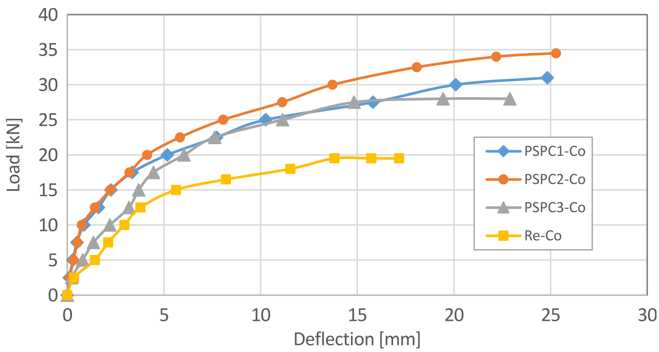

Fig. 4. Comparison of load-deflection curves for tested specimens.

3.2. First crack load and crack width

The slabs are loaded monotonically and monitored closely to specify the first visible cracks. Then, the load continues to increase until the ultimate load. In each stage, the crack width was specified. Moreover, another reading for crack width was taken between these two loads (first visible crack load and ultimate load). Table 3 shows the results obtained.

Table 3. Loads and the corresponding crack's width.

No.	Model's name	Opening's diameter [mm]	Number of openings	Load [kN]	Crack's width [mm]
1	Re-Co	Reinforced by steel bar	–	10	0.482
				15	3.17
				19.5	9.52
2	PSPC1-Co	68	144	8	0.436
				20	1.59
				31	3.55
3	PSPC2-Co	102	64	15	0.66
				20	1.26
				34.5	3.02
4	PSPC3-Co	204	16	9	0.74
				20	3.05
				28	9.79

3.3. Crack pattern

Because of the method used to reinforce two-way concrete slabs, the following approach was adopted to track the mechanism of crack propagation. At the load that the first crack occurred, the cracks are specified in green. At the failure load, the cracks are drawn in red. Between these loads, the cracks are marked in blue. A computer mapping for every stage is presented. Figures 5–8 illustrate the cracks in the Re-Co, PSPC1-Co, PSPC2-Co, and PSPC3-Co specimens, respectively.

a) b) c) d)

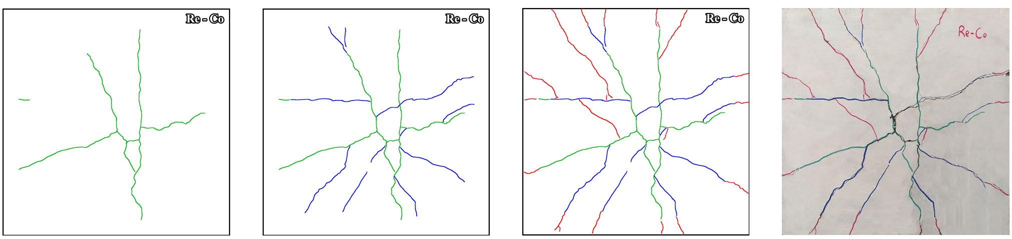

FIG. 5. Crack pattern for Re-Co (tension face): a) computerized mapping tension face – first stage, load: 10 kN, crack width: 0.482 mm; b) computerized mapping tension face – second stage, load: 15 kN, crack width: 3.17 mm; c) computerized mapping, tension face – third stage, load: 19.5 kN, crack width: 9.52 mm; d) actual cracks, tension face – third stage, load: 19.5 kN, crack width: 9.52 mm.

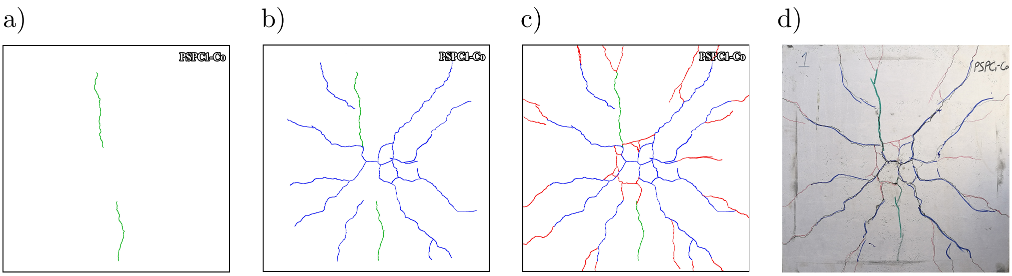

FIG. 6. Crack pattern for PSPC1-Co (tension face): a) computerized mapping, tension face – first stage, load: 8 kN, crack width: 0.436 mm; b) computerized mapping, tension face – second stage, load: 20 kN, ,crack width: 1.59 mm; c) computerized mapping, tension face – third stage, load: 31 kN, crack width: 3.55 mm; d) actual cracks, tension face – third stage, load: 31 kN, crack width: 3.55 mm.

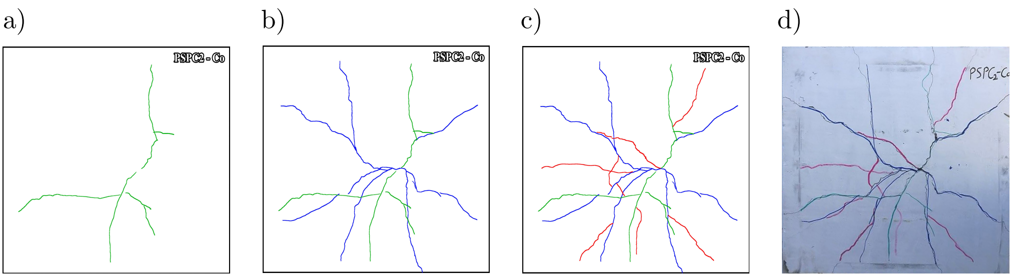

FIG. 7. Crack pattern for PSPC2-Co (tension face): a) computerized mapping, tension face – first stage, load: 15 kN, crack width: 0.66 mm; b) computerized mapping, tension face – second stage, load: 20 kN, crack width: 1.26 mm; c) computerized mapping, tension face – third stage, load: 34.5 kN, crack width: 3.02 mm; d) actual cracks, tension face – third stage, load: 34.5 kN, crack width: 3.02 mm.

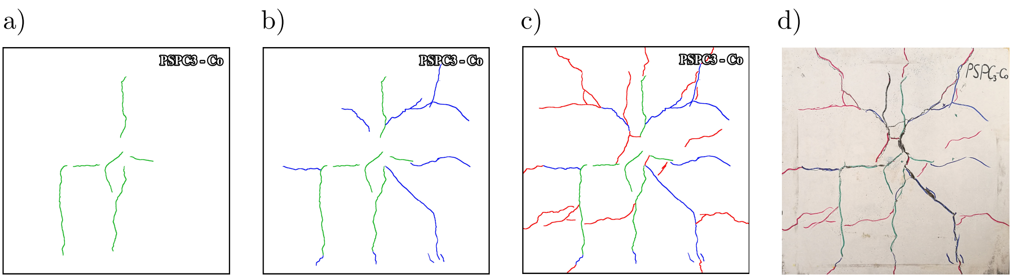

FIG. 8. Crack pattern for PSPC3-Co (tension face): a) computerized mapping, tension face – first stage, load: 9.0 kN, crack width: 0.74 mm; b) computerized mapping, tension face – second stage, load: 20 kN, crack width: 3.05 mm; c) computerized mapping, tension face – third stage, load: 28 kN, crack width: 9.79 mm; d) actual cracks, tension face – third stage, load: 28 kN, crack width: 9.79 mm.

4. Result discussion

The ultimate loads of the PSPC1-Co, PSPC2-Co and PSPC3-Co were 31 kN, 34.5 kN, and 28 kN, respectively, while the ultimate load for the specimens reinforced by the deformed bar (Re-Co) was 19.5 kN. Hence, the specimens PSPC1-Co, PSPC2-Co and PSPC3-Co display higher ultimate resistance load than Re-Co by 58.97%, 76.92%, and 43.59%, respectively.

Furthermore, the slabs reinforced by the perforated steel plate display more stiffness than the one reinforced by traditional reinforcement. PSPC2-Co presents the optimal size of openings for the stiffer slab, as shown in Fig. 4.

Also, the medium size of openings, PSPC2-Co, shows enhancing in the first visible crack load by about 50% more than the specimen reinforced by bar reinforcements. The first crack load was 15 kN, while the first crack load for specimen with traditional reinforcements Re-Co was 10 kN. The increasing or decreasing of opening size will degrade the value of the first crack load. PSPC2-Co first visible crack load is approximately 87.5% higher than PSPC1-Co and 66.67% higher than PSPC3-Co.

5. Conclusions

The proposed reinforcing technique that uses the perforated steel plate provides more ultimate resistance load and stiffer behavior than the traditional method using the deformed steel bar. From the three adopted openings' sizes, the medium size of openings (102 mm with 64 openings) gives the best results compared to the small size (68 mm with 144 openings) and large size (204 mm with 16 openings). The proposed solution is valid in the case of concentrated loads on slabs reinforced by perforated steel plates of relatively small thickness.

References

1. Zhang J.W., Teng J.G., Wong Y.L., Lu Z.T., Behavior of two-way RC slabs externally bonded with steel plate, *Journal of Structural Engineering*, **127**: 390–397, 2001, doi: 10.1061/(ASCE)0733-9445(2001)127:4(390).

2. Ebead U., Marzouk H., Strengthening of two-way slabs using steel plates, *ACI-Structural Journal*, **99-S3**(1): 23–31, 2002, doi: 10.14359/11032.

3. Rasheed L.Sh., Al-Azawi T.K., Experimental analysis of reinforced concrete slabs strengthened with steel plates, *The Iraqi Journal for Mechanical and Material Engineering*, **13**(1): 1–12, 2013.

4. Metwally I.M., Three-dimensional finite element analysis of reinforced concrete slabs strengthened with epoxy-bonded steel plates, *Advances in Concrete Construction*, **2**(2): 91–108, 2014, doi: 10.12989/acc.2014.2.2.091.

5. Elbakry H.M.F., Allam S.M., Punching strengthening of two-way slabs using external steel plates, *Alexandria Engineering Journal*, **54**(4): 1207–1218, 2015, doi: 10.1016/j.aej.2015.09.005.

6. Okamura H., Ouchi M., Self-compacting concrete, *Journal of Advanced Concrete Technology*, **1:** 5–15, 2003, 10.3151/jact.1.5.

7. ACI Committee 237, *Self-Consolidating Concrete*, American Concrete Institute, Farmington Hills, MI 48331, 2007.

8. ACI Committee 318, ACI 318 R-19: *Building Code Requirements for Structural Concrete*, American Concrete Institute, Farmington Hills, MI 48331, 2019.

9. Alwash N.A., Habeeb G.M., Naser F.H., Shear behavior of light weight concrete slab panels reinforced with CFRP bars, *The Iraqi Journal for Mechanical and Material Engineering*, Conference Issue: First International Engineering Conference 2016, University of Babylon, Iraq, pp. 367–385, 2016.

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