Effect of openings on the behaviour of reinforced concrete two-way slabs

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Usually openings are required in RC two-way slabs of buildings where it is necessary for electrical cables, plumbing, fire fighting pipes, and air conditioners. However, this topic was found to be briefly covered in the literature. The usual design practice for the analysis of reinforced concrete slabs with openings is to neglect the effect of openings if their area is less than 10-12% of the total slab area. In this paper an extensive experimental study was conducted in order to investigate the behavior of reinforced concrete two-way slabs with openings in both the elastic range and the post elastic range up to the slab failure. The experimental program included casting, instrumentation, and testing ten reinforced concrete slabs up to failure. Many variables were studied through the experimental program such as: loading pattern; opening location; opening size; opening shape; and finally number of openings. Firstly, two reference slabs were made without any openings and were tested under two different loading patterns. Secondly, four slabs were made provided with one central opening having different sizes. Thirdly, two slabs were made having four small openings near the slab corners. Finally, two slabs were made provided with two rectangular openings. For all tested slabs the initiation and propagation of cracks, cracking and failure loads, and modes of failure were observed and recorded. Vertical deflections and flexural steel strains were measured and recorded. Test results revealed the significant influence of the presence of openings on the behavior of reinforced concrete two-way slabs. The presence of openings led to a significant reduction in the cracking loads and failure loads of tested slabs. Also, it was found that it is much better to provide four small corner openings rather than one central opening having the same total area of the four openings. Furthermore, it was concluded that the loading pattern has a significant influence on the behavior of tested slabs especially those provided with one central opening or two rectangular openings.

دائماً ماتكون الفتحات فى بلاطات المبانى من الأهمية عندما يكون مطلوب إمرار كابلات كهربائية، مواسير تغذية وصرف، مواسير مكافحة الحريق وتكييف الهواء. على الرغم من ذلك فإن هذا الموضوع وجد أنه قد درس بصورة مختصرة فى المراجع المتاحة. وقد جرت العادة عند تصميم البلاطات الخرسانية المسلحة ذات الفتحات أن يتم إهمال تأثير هذه الفتحات إذا كانت مساحتها أقل من ١٠ – ١٢% من المساحة الكلية للبلاطة. فى هذا البحث تم عمل دراسة معملية مكثفة من أجل مناقشة سلوك البلاطات الخرسانية المسلحة ذات الإتجاهين و المزودة بفتحات. تضمن البرنامج العملى صب وتجهيز وإختبار عشرة بلاطات خرسانية مسلحة حتى الإنهيار. تم دراسة تأثير عدة عوامل خلال البرنامج العملى مثل: شكل الأحمال، مكان الفتحة، مقاس الفتحة، شكل الفتحة، وعدد الفتحات. أولاً تم صب و تجهيز بلاطتين مرجعيتين بدون فتحات وتم إختبارهما تحت تأثير شكلين مختلفين للأحمال. ثانياً تم اختيار أربعة بلاطات مزودة بفتحة واحدة فى مركز البلاطة بمقاسات مختلفة. ثالثاً تم اختبار بلاطتين مزودتين بأربعة فتحات صغيرة بالقرب من أركان البلاطة.و أخيراً تم اختبار بلاطتين مزودتين بفتحتين مستطيلتين. لجميع البلاطات المختبرة تم ملاحظة ظهور الشروخ وتتبع تطورها وتم تسجيل أحمال التشريخ. تم قياس وتسجيل سهم الانحناء الرأسى والانفعال فى حديد التسليح. كذلك تم ملاحظة وتسجيل حمل الانهيار وشكل الانهيار. أوضحت النتائج المعملية التأثير الكبير لوجود الفتحات على سلوك البلاطات الخرسانية المسلحة ذات الاتجاهين كما لوحظ ان وجود هذه الفتحات قد أدى إلى نقص كبير فى أحمال التشريخ وأحمال الانهيار للبلاطات المختبرة. كذلك وجد أنه من الأفضل كثيراً تزويد البلاطة بأربعة فتحات صغيرة بالقرب من أركان البلاطة عن تزويدها بفتحة واحدة فى مركز البلاطة بنفس المساحة الكلية للفتحات الأربعة. كذلك وجد أن شكل الأحمال يؤثر تأثيراً كبيراً على سلوك البلاطات خصوصاً إذا كانت مزودة بفتحة فى مركزها أوفتحتين مستطيلتين.

Keywords: Deflection, Openings, Reinforced concrete, Slabs, Two-way

1. Introduction

Usually openings are necessary in two-way slabs of buildings where it is required for electrical cables, plumbing, fire fighting pipes, and air conditioners. Also, openings in two-way slabs are required in the case of industrial buildings and water tanks for the purposes of lighting and ventilation. All multistory buildings require multiple slab penetrations. Larger openings are required for stairs and elevators. However, this topic was found to be briefly covered in the literature. The usual design practice for the analysis of reinforced concrete slabs with openings is to neglect the effect of openings if their area is less than 10-12% of the total slab area. This practice is based on studies conducted in the early sixties regarding the effects of holes on the elastic behavior of plates [1]. The ACI code [2] permits openings of any size in any slab system, provided that an analysis is performed that demonstrates that both strength and serviceability requirements are satisfied [3]. The analysis of slabs with openings is complex and time consuming. Furthermore, the ACI code [2] gives guidelines and limitations for opening locations and size for flat slabs without beams. If the designer satisfies these requirements the analysis could be waived [3]. A brief guidance was presented regarding the locations and size of openings in reinforced concrete two-way slabs [3]. Corner openings are recommended with a size up to 1/4 of the span. Openings adjacent to the beams are not recommended. Furthermore, central openings are permitted with a size up to 1/8 of the span.

Several theoretical investigations were found in the literature regarding the effects of openings on the behavior of reinforced concrete slabs. Non-linear finite element analysis was employed [1]. It was found that openings do not have much effect in the case of slabs subjected to uniformly distributed loads. However, openings should be considered when designing slabs subjected to concentrated loads where the opening ratio are larger than 2.5%. Non-linear finite element analysis was also employed by other researchers in order to study the effect of openings on the behavior of reinforced concrete slabs [4 to 6]. It was found that the presence of openings in reinforced concrete slabs causes a reduction in the ultimate capacity [6]. Such reduction depended on the opening size and position and ranged between 17% and 32%. Yield line analysis was performed for rectangular slabs with central opening [7]. The three possible yield line patterns were analyzed and design diagrams were derived. Furthermore, another theoretical study was found in the literature regarding the behavior of reinforced concrete slabs with a square opening when provided with braces [8].

Several experimental investigations were found in the literature regarding the effect of openings on the behavior of reinforced concrete slabs [9 to 13]. However, all these investigations considered the effect of openings in the case of flat slabs. None of these studies considered two-way reinforced concrete slabs with openings. Furthermore, several investigations were found in the literature considered strengthening of reinforced concrete slabs with openings using Carbon Fiber Reinforced Polymers (CFRP) [14 to 17]. It was concluded that CFRP system proved to be effective in enhancing the load-carrying capacity and stiffness of reinforced concrete slabs with openings, provided that premature failure due to fiber reinforced polymer debonding is excluded.

From the above presented available previous investigations, it is clear that there is a need for more detailed experimental investigation in order to cover all the important aspects of the problem of the presence of openings in reinforced concrete two-way slabs. It was found that previous investigations concentrated on studying the effect of openings in the case of reinforced concrete flat slabs. Very little investigations considered the effect of openings in the case of two-way slabs. Therefore, in this paper an extensive experimental study was conducted in order to investigate the behavior of reinforced concrete two-way slabs with openings in both the elastic range and the post elastic range up to the slab failure. The experimental program included casting, instrumentation, and testing ten reinforced concrete slabs up to failure. Many variables were studied through the experimental program such as: (i) loading pattern; (ii) opening location; (iii) opening size; (iv) opening shape; and finally (v) number of openings. For all tested slabs the initiation and propagation of cracks were observed and cracking loads were recorded. Vertical deflections and flexural steel strains were measured and recorded. Also, failure loads and modes of failure were observed and recorded.

2. Experimental program

An experimental program was conducted in order to study the effect of the presence of openings on the behavior of reinforced concrete two-way slabs. The experimental program included casting, instrumentation, and testing ten reinforced concrete two-way slabs. Tested slabs were divided into two main groups according to the loading pattern. The five slabs in the first group were tested under the effect of four concentrated loads and were all given the symbol “L4”. The other five slabs in the second group were tested under the effect of two concentrated loads and were all given the symbol “L2”. Thus, a comparison between the results of testing the corresponding slabs in the two groups shall yield the effect of loading pattern on the behavior of reinforced concrete slabs with and without openings. All tested slabs were square in plan with a total side length of 1100 mm and a span length of 1000 mm. All tested slabs were simply supported from the four sides. The slab thickness was 50 mm for all tested slabs. All tested slabs were provided with one bottom layer of flexural reinforcement consisting of seven mild steel bars diameter 8 mm in both directions.

The first slab in each of the two groups was made without openings and was given the identification “S-NO-L4” for the slab tested under the effect of four loads and the identification “S-NO-L2” for the slab tested under the effect of two loads. These two slabs were considered as the reference slab for each group. The second slab in the two groups was provided with one central square opening having dimensions 300 mm x 300 mm. These slabs were given the identification “S-CO.3-L4” for the slab tested under the effect of four loads and the identification “S-CO.3-L2” for the slab tested under the effect of two loads. The size of central square opening was increased to 400 mm x 400 mm for the third slab in the two groups. These slabs were given the identification “S-CO.4-L4” for the slab tested under the effect of four loads and the identification “S-CO.4-L2” for the slab tested under the effect of two loads. Four square openings having dimensions 150 mm x 150 mm were provided for the fourth slab in the two groups. These slabs were given the identification “S-FO.15-L4” for the slab tested under the effect of four loads and the identification “S-FO.15-L2” for the slab tested under the effect of two loads. The last fifth slab in the two groups was provided with two rectangular openings having dimensions 150 mm x 300 mm. These slabs were given the identification “S-RO-L4” for the slab tested under the effect of four loads and the identification “S-RO-L2” for the slab tested under the effect of two loads. It should be noted that the total area of openings was kept the same for the second, fourth, and fifth slab in each group although the number and dimensions of the openings were different. Details of tested slabs are shown in figs. 1 and 2 and are listed in table 1.

The concrete mix used for casting the slabs consisted of ordinary Portland cement, natural sand, and broken stones with 20 mm maximum size, and the mix proportions were 1.0: 1.6: 2.55, respectively by weight. The water cement ratio w/c was 0.4. In order to determine concrete strength standard cubes 150x150x150 mm were cast from each concrete batch. These cubes were tested in the same day of testing the corresponding slabs. The average concrete cube compressive strength f_{cu} was 29 Mpa. The 8 mm diameter mild steel bars used for the slabs had a yield and ultimate strength of 250 and 400 MPa, respectively.

The deflection was measured under the concentrated loads by means of four mechanical dial gauges for the slabs in the first group whereas two mechanical dial gauges were used for the slabs in the second group. An electrical strain gauge of 10 mm

Fig. 1. Dimensions for tested slabs under four loads.

Fig. 2. Dimensions for tested slabs under two loads.

Fig. 3. Loading setup for tested slabs.

Table 1
Details of tested reinforced concrete slabs

Group	Slab identification	Description of openings	Size of opening (mm.)	Loading pattern
	S-NO-L4	No openings	N.A.	Four loads
	S-CO.3-L4	One central square opening	300 x 300	Four loads
The first group	S-CO.4-L4	One central square opening	400 x 400	Four loads
	S-FO.15-L4	Four square openings	150 x 150	Four loads
	S-RO-L4	Two rectangular openings	150 x 300	Four loads
	S-NO-L2	No openings	N.A.	Two loads
	S-CO.3-L2	One central square opening	300 x 300	Two loads
The second group	S-CO.4-L2	One central square opening	400 x 400	Two loads
	S-FO.15-L2	Four square openings	150 x 150	Two loads
	S-RO-L2	Two rectangular openings	150 x 300	Two loads

gauge length was used to measure the strain in the bottom flexural reinforcement. All reinforced concrete slabs considered in the experimental program were tested to failure. The load was applied using a hydraulic jack of 200 kN capacity. The load was monitored using an electrical load cell. The load was applied in increments of 2.5 kN up to the failure of each slab. Fig. 3 shows loading setup for tested slabs. For all tested slabs the initiation and propagation of cracks were observed and the cracking loads were recorded. Also, failure loads and modes of failure were observed and recorded. Fig. 4 shows one of the tested slabs under load.

3. Test results and discussions

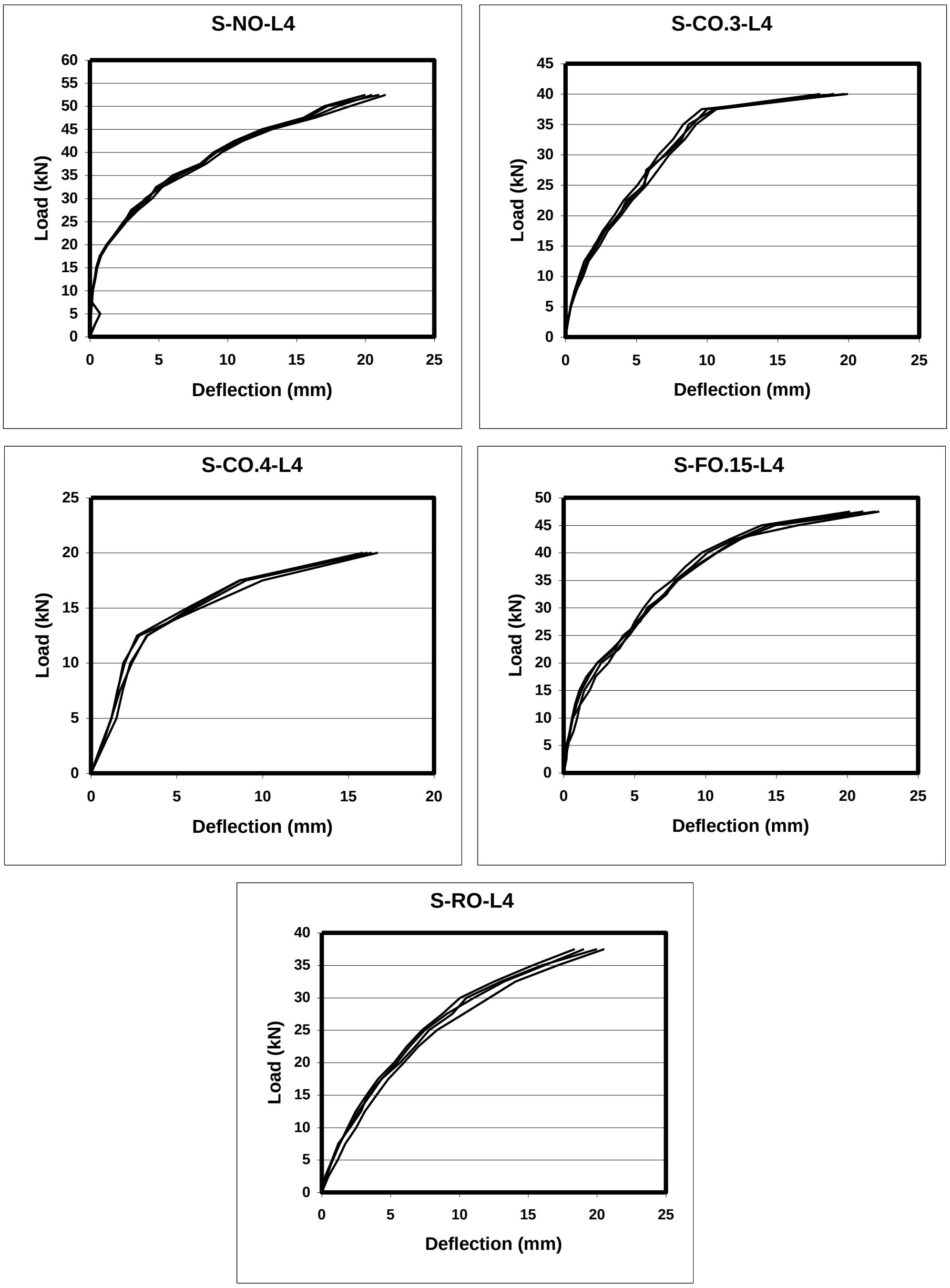
The main objective of the current experimental program was to study the effect of openings on the behavior of reinforced concrete two-way slabs in the elastic range of loading and also in the post-elastic range of loading up to the failure of slabs. In the following sections the behavior of reinforced concrete two-way slabs with openings shall be discussed in detail from the point of view of: (i) deflections; (ii) steel strains; (iii) cracking

Table 2
Test results

Slab identification	Deflection, (mm)		Steel strain		Cracking load (kN)	Failure load (kN)
	Elastic deflection*, δ_e	Deflection at failure load, δ_f	Elastic strain*, ε_e	Strain at failure load, ε_f		
S-NO-L4	0.08	21.47	8	2770	22.5	52.5
S-CO.3-L4	0.34	19.95	61	2990	15.0	40.0
S-CO.4-L4	1.19	16.36	---------	---------	7.5	20.0
S-FO.15-L4	0.20	21.13	40	3040	20.0	47.5
S-RO-L4	0.40	19.06	130	3150	12.5	37.5
S-NO-L2	0.17	20.85	10	2600	20.0	42.5
S-CO.3-L2	0.64	18.68	100	2700	12.5	32.5
S-CO.4-L2	1.73	13.14	---------	---------	5.0	15.0
S-FO.15-L2	0.53	19.26	47	2600	17.5	35.0
S-RO-L2	1.00	16.73	185	3000	10.0	30.0

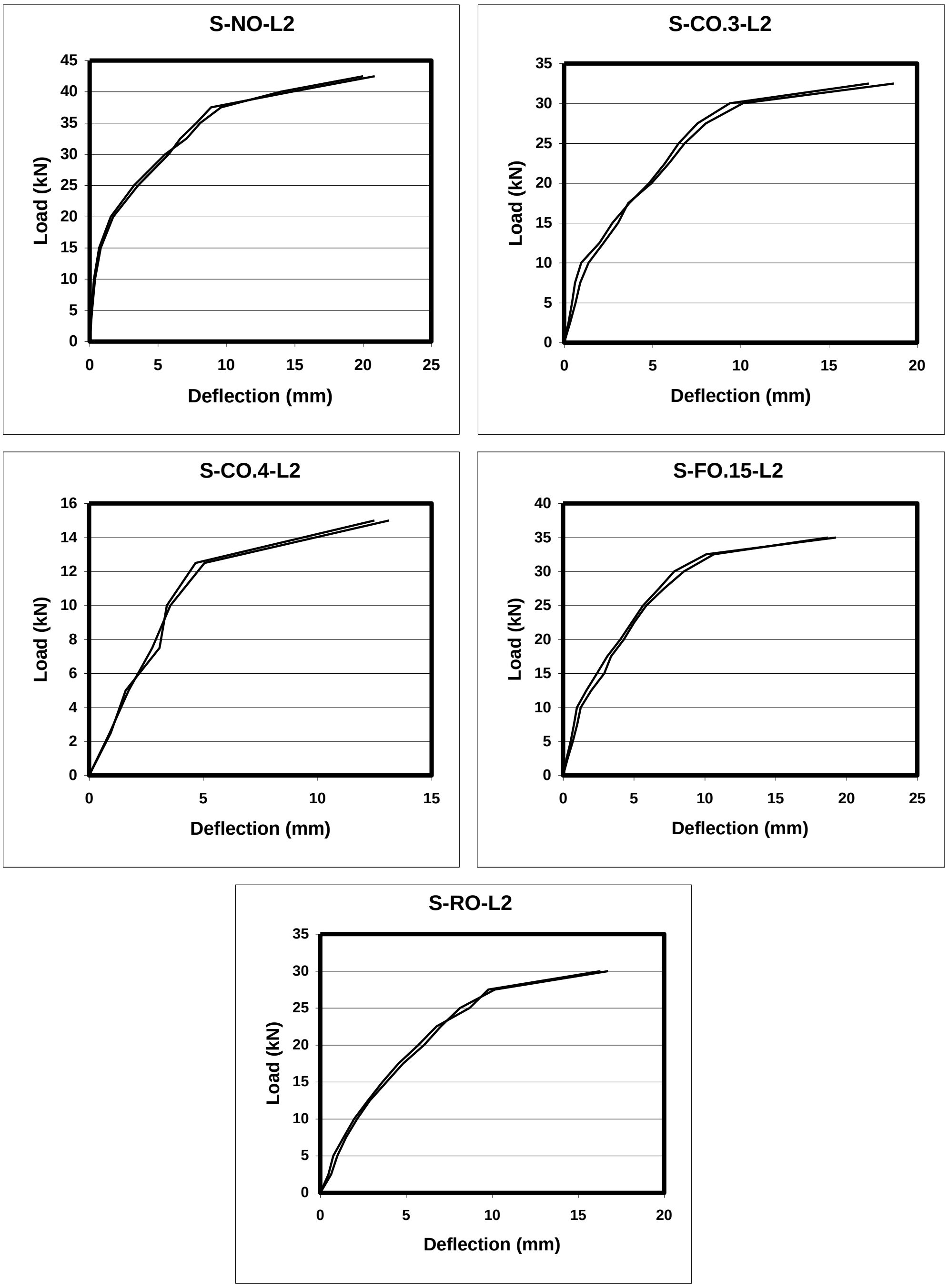
- δ_e and ε_e = Deflection and steel strain in the elastic range at a load = 5.0 kN.

Fig. 4. One of the tested slabs under load.



Note: The four curves in each diagram represent the readings of the dials under the four loading points.

Fig. 5. Load-deflection relationships for slabs tested under four loads.



Note: The two curves in each diagram represent the readings of the dials under the two loading points.

Fig. 6. Load-deflection relationship for slabs tested under two loads.

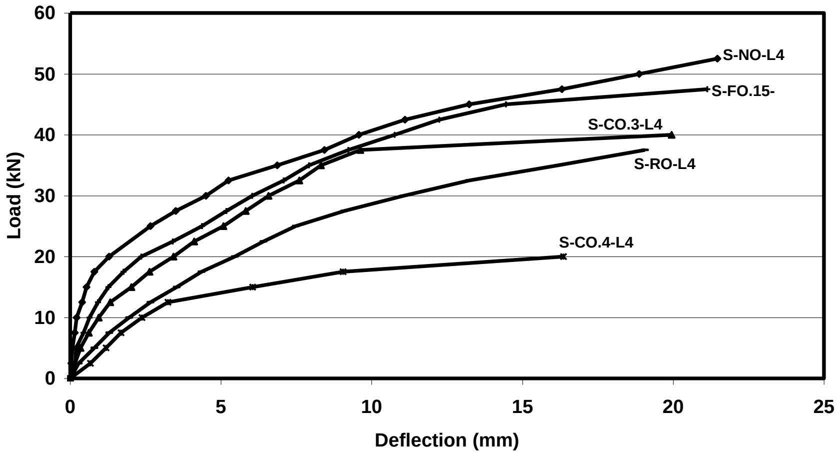


Fig. 7. Effect of openings on load-deflection relationships for slabs tested under four loads.

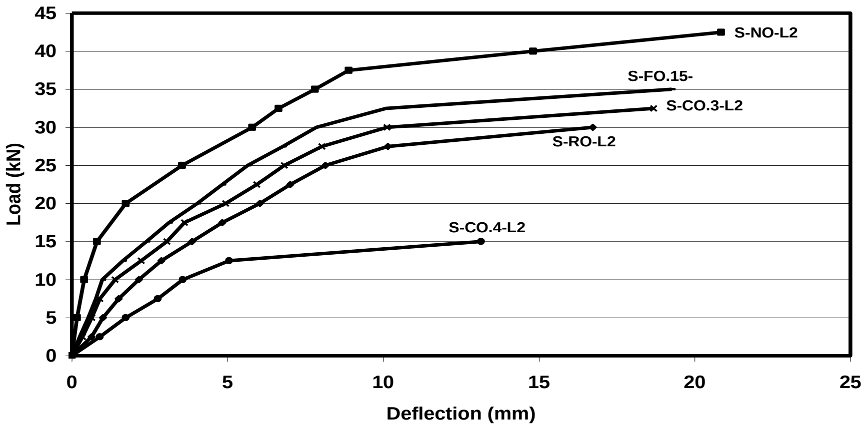


Fig. 8. Effect of openings on load-deflection relationships for slabs tested under two loads.

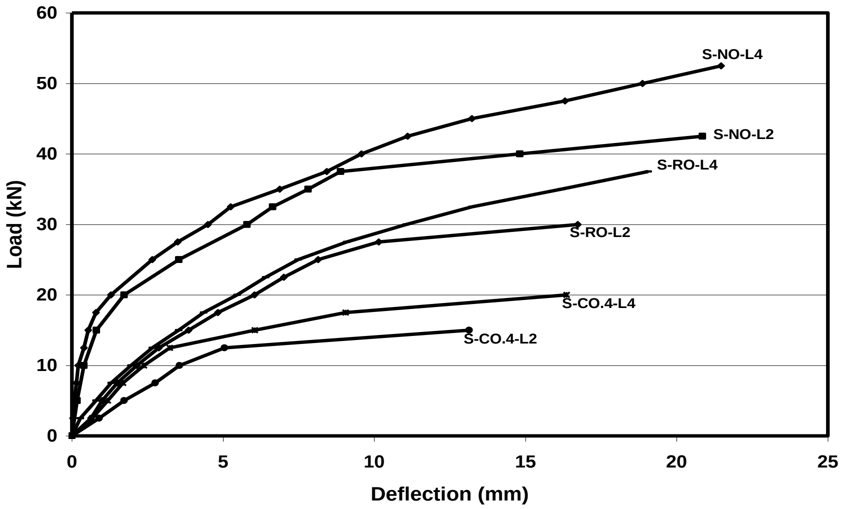


Fig. 9. Effect of loading pattern on load-deflection relationships for some of the tested slabs.

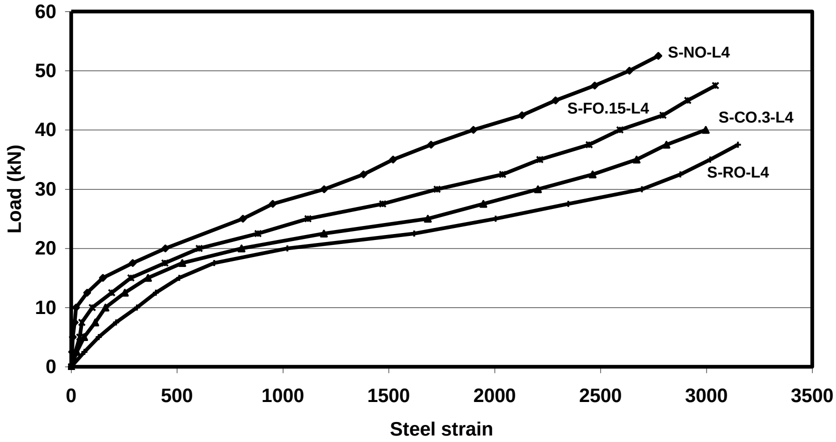


Fig. 10. Load-steel strain relationships for slabs tested under four loads.

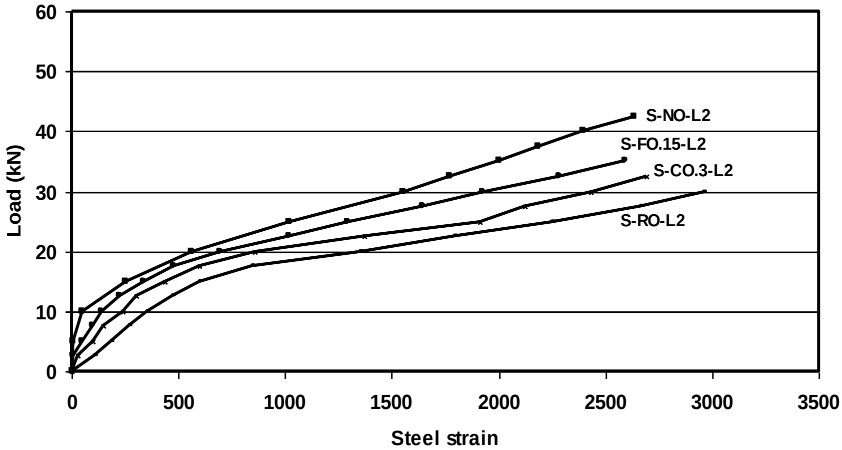


Fig. 11. Load-steel strain relationships for slabs tested under two loads.

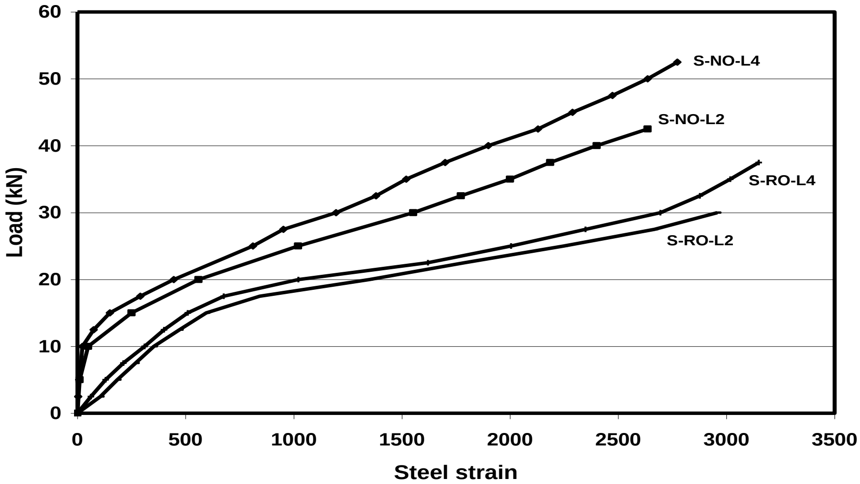


Fig. 12. Effect of loading pattern on load-steel strain relationships for some of the tested slabs.

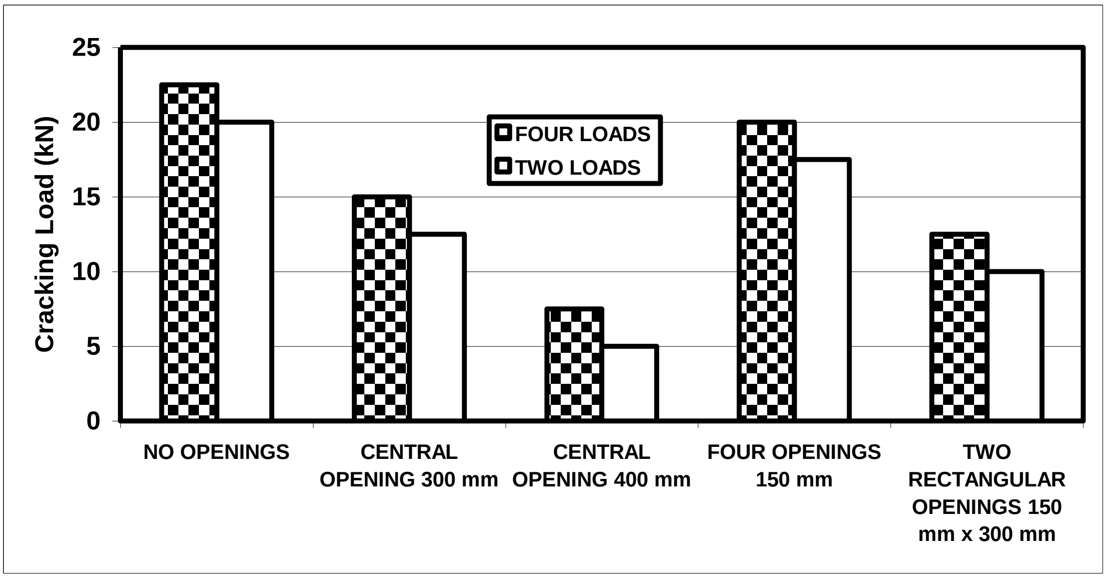


Fig. 13. Effect of openings and loading patterns on cracking loads of tested slabs.

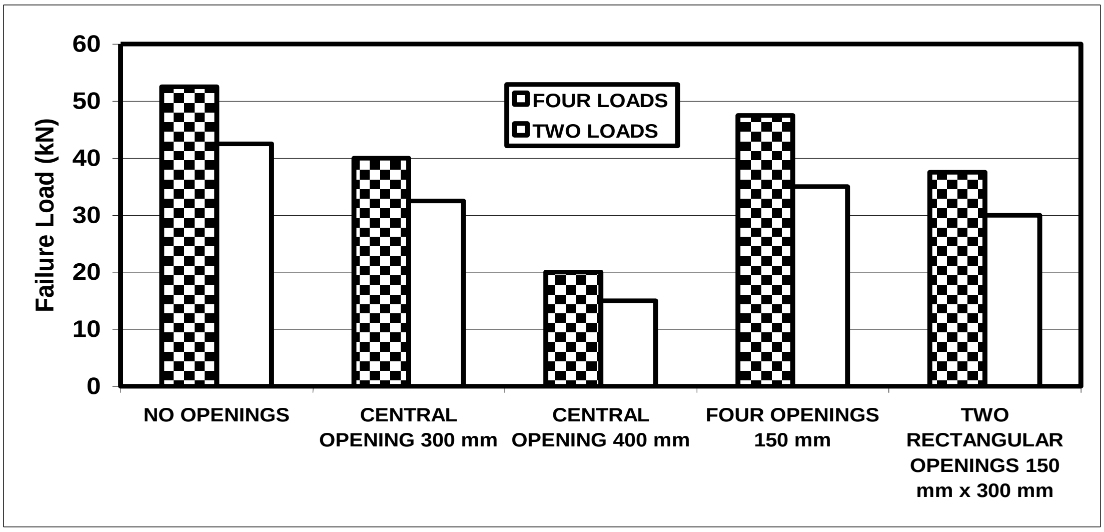


Fig. 14. Effect of openings and loading patterns on failure loads of tested slabs.

Fig. 15. Cracking patterns of slabs tested under four loads after failure.

Fig. 16. Cracking patterns of slabs tested under two loads after failure.

loads; (iv) failure loads; and finally (v) failure modes and cracking patterns. The effects of the following significant parameters shall be investigated: (i) loading pattern; (ii) opening location; (iii) opening size; (iv) opening shape; and finally (v) number of openings. The effect of loading pattern shall always be detected when comparing the results of testing slabs in the first group to those of the corresponding slabs in the second group. The effect of the presence of openings shall be determined when comparing the results of testing the first slab in each group (reference slab without openings) to those of the second, third, fourth, and fifth slabs having openings. The effect of size of opening shall be indicated when comparing the results of testing the second slab in each group (central opening 300 mm x 300 mm) to those of testing the third slab (central opening 400 mm x 400 mm). The effect of number of openings shall be detected when comparing the results of testing the second slab in each group (central opening 300 mm x 300 mm) to those of testing the fourth slab (four openings 150 mm x 150 mm). Finally, the effect of opening shape shall be determined when comparing the results of testing the second slab in each group (central opening 300 mm x 300 mm) to those of testing the fifth slab (two rectangular openings 150 mm x 300 mm). It should be noted that the total area of openings was kept constant for the second, fourth, and the fifth slabs in the two groups. Such openings area represents 9% of the total slab area. However, such area was increased to 16% of the total slab area for the third slab in each group.

The experimental test results are presented in table 2. for all tested slabs. The results include: (i) deflections in the elastic range δ_e at a load = 5.0 kN; (ii) deflections at failure loads δ_f; (iii) steel strains in the elastic range ε_e at a load = 5.0 kN; (iv) steel strains at failure loads ε_f; (v) cracking loads; and finally (vi) failure loads. Fig. 5 shows load-deflection relationships for slabs tested under four loads. Fig. 6 shows load-deflection relationships for slabs tested under two loads. Fig. 7 presents the effect of openings on load-deflection relationships for slabs tested under four loads. Fig. 8 presents the effect of openings on load-deflection relationships for slabs tested under two loads. Fig. 9 shows the effect of loading pattern on load-deflection relationships for some of the tested slabs. Fig. 10 presents load-steel strain relationships for slabs tested under four loads. Fig. 11 presents load-steel strain relationships for slabs tested under two loads. Fig. 12 shows the effect of loading pattern on load-steel strain relationships for some of the tested slabs. Fig. 13 presents the effect of openings and loading pattern on cracking loads of tested slabs. Fig. 14 shows the effect of openings and loading pattern on failure loads of tested slabs. Fig. 15 presents cracking patterns of slabs tested under four loads after failure. Fig. 16 shows cracking patterns of slabs tested under two loads after failure. Fig. 17 shows crushing of concrete at the top surface of one of the tested slabs after failure.

3.1. Deflections

Deflections of tested slabs were measured under the concentrated loads at four points for slabs in the first group tested under the effect of four loads and at two points for slabs in the second group tested under the effect of two loads. It was found that deflections were significantly affected by the loading pattern. As expected, deflections in the elastic range increased significantly in the case of slabs tested under the effect of two loads in comparison to those tested under the effect of four loads. For example, in the case of slabs without openings the deflection in the elastic range increased from 0.08 mm for slab (S-NO-L4) tested under four loads to 0.17 mm for slab (S-NO-L2) tested under two loads, representing about 113 % increase. Also, in the case of slabs with openings the elastic deflection increased for slabs tested under two loads in comparison to those slabs tested under four loads. Such increase in the deflection in the elastic range was between 45% and 165%, depending on the openings size, number, and shape. Furthermore, it was found that the deflection in the post-elastic range of loading at any given load increased in the case of slabs tested under the effect of two loads than that in the case of slabs tested under four loads as shown in fig. 9. However, different observations were found for the effect of loading pattern on the deflection at failure load. Such deflection decreased in the case of slabs tested under the effect of two loads in comparison to those for slabs tested under the effect of four loads. For example, in the case of slabs without openings the deflection at failure load decreased from 21.47 mm for slab (S-NO-L4) tested under four loads to 20.85 mm for slab (S-NO-L2) tested under two loads, representing about 3% decrease. However, such decrease in the deflection at failure load in the case of slabs tested under two loads was much more significant in the case of slabs with openings. In this case the decrease in the deflection at failure load ranged between 6% and 20%, depending on the openings size, number, and shape.

The presence of openings in tested slabs significantly affected the deflection in the elastic range of loading, post-elastic range of loading, and also at slab failure load. In the case of slabs tested under the effect of four loads the deflection in the elastic range of loading increased from 0.08 mm for the reference slab without openings (S-NO-L4) to 0.34 mm for slab (S-CO.3-L4) having central square opening 300 mm x 300 mm, representing about 325% increase in the deflection in the elastic range as a result of the presence of the opening. Furthermore, on increasing the central opening size to 400 mm x 400 mm (S-CO.4-L4) the deflection in the elastic range increased to 1.19 mm, representing about 1400 % increase in comparison to that of the reference slab without opening (S-NO-L4) and about 250 % increase in comparison to slab (S-CO.3-L4) having central opening 300 mm x 300 mm. Such increase in the deflection in the elastic range as a result of the presence of central opening or as a result of the increase in the central opening size was also observed in the post-elastic range of loading at any given load as shown in fig. 7. Therefore, it is concluded herein that the deflection in the elastic and post-elastic range of loading significantly increase as a result of the presence of central opening. Furthermore, such deflection in the elastic range is very sensitive to an increase in the size of central opening. The situation regarding the deflection in the elastic and post-elastic range of loading was significantly enhanced in the case of slab (S-FO.15-L4) provided with four square openings 150 mm x 150 mm. In this case the deflection in the elastic range of loading increased by only 150% over that of the reference slab without openings (S-NO-L4) in comparison to 325% in the case of slab having central opening (S-CO.3-L4) although the openings in both slabs had the same area. Therefore, it is concluded herein that design engineers should avoid providing slabs with central openings. It is recommended herein to provide slabs with four small openings near corners having the same area as that of one central opening. Also, it was found that providing slabs with two rectangular openings having the same area of one central opening do not enhance the slab deflection in both the elastic and post-elastic range of loading. It should be noted that deflection of slabs at failure load decreased as a result of the presence of openings. Furthermore, deflection at failure load decreased as a result of increasing the opening size. Similar observations were found for slabs in the second group tested under the effect of two loads regarding the effect of openings on the deflection in the elastic range of loading, post-elastic range of loading, and deflection at slab failure load.

3.2. Steel strains

Steel strains were measured for the bottom flexural reinforcement of all tested reinforced concrete two-way slabs. It was observed that the steel strain was significantly affected by the presence of openings. Also, the size, number, and shape of openings remarkably affected the steel strain in the bottom flexural reinforcement. Examining the results presented in table 2. regarding the steel strain in the elastic range of loading at a load = 5.0 kN for the slabs tested in the first group under the effect of four concentrated loads, one can observe the following: (i) for the reference slab without openings (S-NO-L4) the steel strain in the elastic range was equal to 8.0; (ii) as a result of providing a central square opening 300 mm x 300 mm (S-CO.3-L4) the steel strain in the elastic range increased to 61.0, representing about 663% increase; (iii) however, as a result of providing four small square openings near corners having the same area as the central opening (S-FO.15-L4), the steel strain in the elastic range increased to only 40.0 representing about 400% increase; and (iv) on providing two rectangular openings having the same area as the previous openings (S-RO-L4) the steel strain dramatically increased to 130.0, representing about 1525% increase.

Furthermore, the following can be observed regarding the steel strain in the elastic range of loading at a load = 5.0 kN for the slabs tested in the second group under the effect of two concentrated loads: (i) for the reference slab without openings (S-NO-L2) the steel strain in the elastic range was equal to 10.0; (ii) as a result of the presence of one central square opening 300 mm x 300 mm (S-CO.3-L2) the steel strain in the elastic range increased to 100.0, representing about 900% increase; (iii) however, as a result of providing four small square openings near corners having the same area as the central opening (S-FO.15-L2), the steel strain in the elastic range increased to only 47.0 representing about 370% increase; and (iv) in the case of providing two rectangular openings having the same area as the previous openings (S-RO-L2) the steel strain dramatically increased to 185.0, representing about 1750% increase. Therefore, the following can be concluded herein regarding the effect of openings on the steel strain in the bottom flexural reinforcement: (i) the steel strain in the elastic range of loading increases significantly as a result of the presence of openings in reinforced concrete two-way slabs; (ii) such strain is very sensitive to a change in the openings configuration in terms of number and shape of openings; (iii) the worst openings configuration that dramatically increases the steel strain is the rectangular openings followed by the central opening; (iv) the best openings configuration that controls the steel strain in the bottom flexural reinforcement is the four small openings near the slab corners; (v) the rate of increase in the steel strain in the bottom flexural reinforcement as a result of the presence of openings is much greater in the case of slabs tested under the effect of two concentrated loads than that in the case of slabs tested under the effect of four concentrated loads; (vi) the observations mentioned above for the significant effect of the openings on the steel strain in the elastic range of loading was also found to be applicable for the steel strain in the post-elastic range of loading at any given load; and (vii) however, the effect of the presence of openings on the steel strain at failure load was found to be much less significant. The presence of openings led to a marginal increase in the steel strain at failure load.

The loading pattern also significantly affected the steel strain in the bottom flexural reinforcement for tested reinforced concrete two-way slabs. The following can be observed regarding the effect of loading pattern on the steel strain in the elastic range of loading: (i) for the reference slabs without openings the steel strain increased from 8.0 in the case of slab (S-NO-L4) tested under the effect of four concentrated loads to 10.0 for slab (S-NO-L2) tested under the effect of two concentrated loads, representing about 25% increase; (ii) in the case of slabs having one central opening 300 mm x 300 mm the steel strain increased from 61.0 in the case of slab (S-CO.3-L4) tested under the effect of four concentrated loads to 100.0 for slab (S-CO.3-L2) tested under the effect of two concentrated loads, representing about 64% increase; (iii) in the case of slabs provided with four small openings near slab corners the steel strain increased from 40.0 in the case of slab (S-FO.15-L4) tested under the effect of four concentrated loads to 47.0 for slab (S-FO.15-L2) tested under the effect of two concentrated loads, representing about 17.5% increase; and (iv) for the slabs provided with two rectangular openings the steel strain increased from 130.0 in the case of slab (S-RO-L4) tested under the effect of four concentrated loads to 185.0 for slab (S-RO-L2) tested under the effect of two concentrated loads, representing about 42.3% increase. Therefore, it can be concluded herein that generally the application of two concentrated loads rather than four concentrated loads leads to a significant increase in the steel strain in the bottom flexural reinforcement in the elastic range of loading. It can be also concluded that such rate of increase in the steel strain in the elastic range as a result of the application of two concentrated loads was much less significant in the case of slabs without openings and slabs provided with four small openings near the slab corners. Much more significant rate of increase in the steel strain in the elastic range as a result of the application of two concentrated loads was observed in the case of slabs provided with one square central opening or two rectangular openings.

It should be noted that these observations regarding the effect of the loading pattern on the steel strain in the elastic range are also applicable in the post-elastic range of loading. However, marginal decrease was observed in the steel strain in the bottom flexural reinforcement at failure load as a result of applying two concentrated loads rather than four concentrated loads. Such decrease was as follows: (i) for the reference slabs without openings the steel strain at failure load decreased from 2770 in the case of slab (S-NO-L4) tested under the effect of four concentrated loads to 2600 for slab (S-NO-L2) tested under the effect of two concentrated loads, representing about 6% decrease; (ii) in the case of slabs having one central opening 300 mm x 300 mm the steel strain at failure load decreased from 2990 in the case of slab (S-CO.3-L4) tested under the effect of four concentrated loads to 2700 for slab (S-CO.3-L2) tested under the effect of two concentrated loads, representing about 10% decrease; (iii) in the case of slabs provided with four small openings near slab corners the steel strain at failure load decreased from 3040 in the case of slab (S-FO.15-L4) tested under the effect of four concentrated loads to 2600 for slab (S-FO.15-L2) tested under the effect of two concentrated loads, representing about 14% decrease; and (iv) for the slabs provided with two rectangular openings the steel strain at failure load decreased from 3150 in the case of slab (S-RO-L4) tested under the effect of four concentrated loads to 3000 for slab (S-RO-L2) tested under the effect of two concentrated loads, representing about 5% decrease.

3.3. Cracking loads

Cracking loads are listed in Table 2. for all tested slabs. Also, fig. 13 shows the effect of openings and loading patterns on cracking loads of tested slabs. It was found that cracking loads were significantly affected by the loading pattern but were severely affected by the openings. The first crack was observed for the reference slab without openings (S-NO-L4) tested under the effect of four concentrated loads at a load 22.5 kN. Providing one central opening 300 mm x 300 mm (S-CO.3-L4) led to a decrease in the cracking load to 15.0 kN, representing about 33% decrease. However, on increasing the size of central opening to 400 mm x 400 mm (S-CO.4-L4) the cracking load dramatically reduced to only 7.5 kN, representing about 67% decrease. The cracking load raised again to 20.0 kN for the slab provided with four small openings near the slab corners (S-FO.15-L4) and was equal to 12.5 kN for the slab provided with two rectangular openings (S-RO-L4). Furthermore, for the slabs in the second group tested under the effect of two concentrated loads the following was observed: (i) for the reference slab without opening (S-NO-L2) the cracking load was equal to 20.0 kN; (ii) the cracking load decreased for the slab provided with one central opening 300 mm x 300 mm (S-CO.3-L2) to 12.5 kN, representing about 37% decrease; (iii) on increasing the size of central opening to 400 mm x 400 mm (S-CO.4-L2) the cracking load decreased to only 5.0 kN, representing about 75% decrease compared to the reference slab without opening; (iv) for the slab provided with four small openings near the slab corners (S-FO.15-L2) the cracking load was equal to 17.5 kN which is less than that of the reference slab by only 12%; and (v) the cracking load for the slab provided with two rectangular openings (S-RO-L2) was equal to 10.0 kN which is less than that of the reference slab by 50%.

Therefore, it can be concluded herein that the cracking loads of reinforced concrete two-way slabs are very sensitive to the presence of openings. Significant reductions in the cracking loads were observed for the slabs provided with one central opening especially when the size of such opening is large. Significant reduction in the cracking load was also observed in the case of slab provided with two rectangular openings. However, only marginal reduction in the cracking load was observed in the case of slab provided with four small openings near the slab corners. From the point of view of cracking loads the favorable configuration of the openings is the four small openings near the slab corners. Furthermore, it was found that reference slabs made without openings and those provided with four small openings near the slab corners cracked at loads representing 42% to 50% of the slabs failure loads. However, all other slabs provided with openings having different configurations cracked at loads representing 33% to 38% of the slabs failure loads.

The loading pattern also affected the cracking loads of tested slabs. The following was observed: (i) for the reference slabs without openings the cracking load decreased from 22.5 kN for the slab tested under the effect of four concentrated loads (S-NO-L4) to 20.0 kN for the slab tested under the effect of two loads (S-NO-L2), representing about 11% decrease; (ii) for the slabs provided with a central opening 300 mm x 300 mm such decrease was about 17%; (iii) on increasing the size of central opening to 400 mm x 400 mm such decrease raised to 33%; (iv) in the case of slabs provided with four small openings near the slab corners the decrease in the cracking load as a result of loading pattern was about 12%; and (v) such decrease was about 20% for the slabs provided with two rectangular openings. Therefore, it can be concluded herein that the effect of loading pattern on the slab cracking load is marginal in the case of reference slabs without openings and slabs provided with four small openings near the slab corners. However, such effect becomes significant in the case of slabs provided with one central opening or slabs provided with two rectangular openings. It should be noted that the effect of loading pattern on the cracking load becomes severe with increasing the size of the central opening.

3.4. Failure loads

Table 2 presents failure loads for all tested slabs. Fig. 14 shows the effect of openings and loading patterns on the failure loads of tested slabs. The effect of loading pattern on the failure loads of tested slabs was found to be different than that previously described for the cracking loads. For the reference slabs without openings the failure load decreased from 52.5 kN for the slab tested under the effect of four concentrated loads (S-NO-L4) to 42.5 kN for the slab tested under the effect of two concentrated loads (S-NO-L2), representing about 19% decrease. The same percentage of reduction was found in the case of slabs provided with one central opening 300 mm x 300 mm. However, such percentage of reduction raised to 25% and 26% for the slab provided with one central opening 400 mm x 400 mm and the slab provided with four small openings near the slab corners, respectively. For the slabs having two rectangular openings the failure load decreased from 37.5 kN for the slab tested under the effect of four concentrated loads (S-RO-L4) to 30.0 kN for the slab tested under the effect of two concentrated loads (S-RO-L2), representing about 20% decrease.

The effect of openings on the failure loads of tested slabs was in accordance with that previously described for the cracking loads. The following can be observed regarding the effect of openings on the failure loads of slabs in the first group tested under the effect of four concentrated loads: (i) for the reference slab without opening (S-NO-L4) the failure load was equal to 52.5 kN; (ii) for the slab provided with one central opening 300 mm x 300 mm (S-CO.3-L4) the failure load decreased to 40.0 kN, representing about 31% decrease; (iii) on increasing the size of central opening to 400 mm x 400 mm (S-CO.4-L4) the failure load decreased to 20.0 kN, representing about 62% decrease; (iv) in the case of slab provided with four small openings near the slab corners (S-FO.15-L4) the failure load was equal to 47.5 kN representing about 9% decrease compared to the reference slab; and (v) for the slab provided with two rectangular openings (S-RO-L4) the failure load decreased to 37.5 kN, representing about 29% decrease.

Similar observations were found for the effect of openings on the failure loads of slabs in the second group tested under the effect of two concentrated loads. Therefore, it can be concluded herein that the presence of openings is one of the most important parameters that affects the failure loads of reinforced concrete two-way slabs. Marginal reduction was observed in the failure loads of slabs provided with four small openings near the slab corners which supports the previous findings that this is the favorable openings configuration. However, significant reduction in the failure loads was observed for the slabs provided with one central opening 300 mm x 300 mm and the slabs provided with two rectangular openings. Furthermore, severe reduction in the failure loads was observed for the slabs provided with one central opening 400 mm x 400 mm. From the point of view of failure loads, design engineers should avoid providing reinforced concrete two-way slabs with central openings or rectangular openings. It is recommended instead to provide the slab with four small openings near the slab corners having the same total area as the central opening or the rectangular openings.

3.5. Failure modes and cracking patterns

For all tested reinforced concrete two-way slabs the initiation and propagation of cracks were observed and modes of failure were detected. Cracking patterns after failure are shown in fig. 15 for slabs in the first group tested under the effect of four loads. Cracking patterns after failure are shown in fig. 16 for slabs in the second group tested under the effect of two loads. For the reference slabs without openings (S-NO-L4) and (S-NO-L2) a crack started firstly on the bottom surface of the slab initiating from the corner of one of the loading plates towards the slab corner. On increasing the load the width and length of the previous crack increased and another cracks were observed starting from the corners of the other loading plates towards the other slab corners and another crack was observed between each two loads perpendicular to the loading plates. On increasing the load further the length and width of the previous cracks increased and new cracks were observed parallel to the support lines. At failure, the width and length of all previous cracks increased significantly and more lines of cracks appeared. The mode of failure of the reference slabs was flexural failure by yielding of bottom reinforcement followed by concrete crushing at the top surface of the slab.

In the case of slabs provided with one central opening the first crack was observed starting from one of the openings corner towards the slab corner. On increasing the load the length and width of the previous crack increased and another cracks were observed all starting from the other opening corners towards the slab corners. On increasing the load further the length and width of the previous cracks increase significantly and another cracks were observed starting from the sides of openings and from the loading plates towards the support lines. At failure, the length and width of all previous cracks increased significantly and several crack lines appeared. However, different observations were found for the initiation and propagation of cracks in the case of slabs provided with four small openings near the slab corners (S-FO.15-L4) and (S-FO.15-L2). In this case the first crack was observed between the loading plates. On increasing the load cracks were observed starting from the loading plates towards the support lines and also towards the openings. On increasing the load further the length and width of previous cracks increased and another cracks were observed starting from the corners of the openings towards the slab corners and towards the support lines. At failure, the length and width of all previous cracks increased significantly and several cracks appeared and lines of cracks were observed parallel to the support lines. In the case of slabs provided with two rectangular openings (S-RO-L4) and (S-RO-L2) the first crack was observed starting from the opening corners towards the support lines. On increasing the load the length and width of the previous cracks increased and another crack was observed between the loading plates. On increasing the load further many cracks were observed starting from the openings and the loading plates towards the slab corners and support lines. At failure, the length and width of all previous cracks increased significantly and several cracks appeared and lines of cracks were observed parallel to the support lines. It should be noted that the mode of failure of tested slabs was not affected by the presence of openings or by the loading pattern. In all cases the mode of failure was flexural failure by yielding of bottom reinforcement followed by concrete crushing at the top surface of the slab, as shown in fig. 17.

4. Summary and conclusions

Detailed literature review was conducted including all available previous experimental and theoretical investigations on the effect of the presence of openings on the behavior of reinforced concrete slabs. It was found that there is a need for more detailed experimental investigation in order to cover all the important aspects of the problem of the presence of openings in reinforced concrete two-way slabs. It was found that previous investigations concentrated on studying the effect of openings in the case of reinforced concrete flat slabs. Very little investigations considered the effect of openings in the case of two-way slabs. In this paper an extensive experimental study was conducted in order to investigate the behavior of reinforced concrete two-way slabs with openings in both the elastic range and the post elastic range up to the slab failure. The experimental program included casting, instrumentation, and testing ten reinforced concrete slabs up to failure. Many variables were studied through the experimental program such as: (i) loading pattern; (ii) opening location; (iii) opening size; (iv) opening shape; and finally (v) number of openings. For all tested slabs the initiation and propagation of cracks were observed and cracking loads were recorded. Vertical deflections and flexural steel strains were measured and recorded. Also, failure loads and modes of failure were observed and recorded. Based on this study the following conclusions were drawn:

1. Deflections in the elastic range and post-elastic range of loading increased significantly in the case of slabs tested under the effect of two loads in comparison to those tested under the effect of four loads, for slabs without and with openings. However, different observations were found for the effect of loading pattern on the deflection at failure load. Such deflection decreased in the case of slabs tested under the effect of two loads in comparison to those for slabs tested under the effect of four loads.

2.

Fig. 17. Crushing of concrete at the top surface of one of the tested slabs after failure.

2. The deflection in the elastic and post-elastic range of loading significantly increased as a result of the presence of central opening. Furthermore, such deflection is very sensitive to an increase in the size of central opening. The situation regarding the deflection in the elastic and post-elastic range of loading was significantly enhanced in the case of slab provided with four small square openings having the same area as one central opening.
3. Design engineers should avoid providing slabs with central openings. It is recommended herein to provide slabs with four small openings near corners having the same area as that of one central opening. Furthermore, providing slabs with two rectangular openings having the same area of one central opening do not enhance the slab deflection in both the elastic and post-elastic range of loading.
4. Deflection of slabs at failure load decreased as a result of the presence of openings. Furthermore, deflection at failure load decreased as a result of increasing the opening size.
5. The steel strain in the bottom flexural reinforcement in the elastic range of loading increases significantly as a result of the presence of openings in reinforced concrete two-way slabs. Such strain is very sensitive to a change in the openings configuration in terms of number and shape of openings.
6. The worst openings configuration that dramatically increases the steel strain is the

rectangular openings followed by the central opening. The best openings configuration that controls the steel strain in the bottom flexural reinforcement is the four small openings near the slab corners.

7. The rate of increase in the steel strain in the bottom flexural reinforcement as a result of the presence of openings is much greater in the case of slabs tested under the effect of two concentrated loads than that in the case of slabs tested under the effect of four concentrated loads.

8. The effect of the presence of openings on increasing the steel strain in the bottom flexural reinforcement was also found to be significant in the post-elastic range of loading at any given load. However, the effect of the presence of openings on the steel strain at failure load was found to be much less significant. The presence of openings led to a marginal increase in the steel strain at failure load.

9. Generally the application of two concentrated loads rather than four concentrated loads leads to a significant increase in the steel strain in the bottom flexural reinforcement in the elastic range of loading. Such rate of increase in the steel strain in the elastic range as a result of the application of two concentrated loads was much less significant in the case of slabs without openings and slabs provided with four small openings near the slab corners. Much more significant rate of increase in the steel strain in the elastic range as a result of the application of two concentrated loads was observed in the case of slabs provided with one square central opening or two rectangular openings.

10. The application of two concentrated loads rather than four concentrated loads leads to a significant increase in the steel strain in the bottom flexural reinforcement in the post-elastic range of loading at any given load. However, marginal decrease was observed in the steel strain in the bottom flexural reinforcement at failure load as a result of applying two concentrated loads rather than four concentrated loads.

11. The cracking loads of reinforced concrete two-way slabs are very sensitive to the presence of openings. Significant reductions in the cracking loads were observed for the slabs provided with one central opening especially when the size of such opening is large. Significant reduction in the cracking load was also observed in the case of slab provided with two rectangular openings. However, only marginal reduction in the cracking load was observed in the case of slab provided with four small openings near the slab corners.

12. From the point of view of cracking loads the favorable configuration of the openings is the four small openings near the slab corners. Reference slabs made without openings and those provided with four small openings near the slab corners cracked at loads representing 42% to 50% of the slabs failure loads. However, all other slabs provided with openings having different configurations cracked at loads representing 33% to 38% of the slabs failure loads.

13. The effect of loading pattern on the slab cracking load is marginal in the case of reference slabs without openings and slabs provided with four small openings near the slab corners. However, such effect becomes significant in the case of slabs provided with one central opening or slabs provided with two rectangular openings. The effect of loading pattern on the cracking load becomes severe with increasing the size of the central opening.

14. The presence of openings is one of the most important parameters that affects the failure loads of reinforced concrete two-way slabs. Marginal reduction was observed in the failure loads of slabs provided with four small openings near the slab corners. Significant reductions in the failure loads were observed for the slabs provided with openings having any other configuration.

15. From the point of view of failure loads, design engineers should avoid providing reinforced concrete two-way slabs with central openings or rectangular openings. It is recommended instead to provide the slab with four small openings near the slab corners having the same total area as the central opening or the rectangular openings.

16. Although the sequence of crack initiation and propagation was significantly affected by the presence of openings and was also affected by the configuration of openings. However, the mode of failure of tested slabs was not affected

by the presence of openings or by the loading pattern. In all cases the mode of failure was flexural failure by yielding of bottom reinforcement followed by concrete crushing at the top surface of the slab.

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