Experimental behavior of flat slabs with openings under the effect of concentrated loads

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Due to the difficulty of theoretical analysis of reinforced concrete flat slabs especially when there is an opening in these slabs, the experimental investigation still an efficient method to explore their behavior. An experimental study for these slabs can overcome this difficulty and give a correct expectation about the behavior of similar slabs. This paper presents an experimental study on the behavior of flat slabs containing openings at different locations whether they are rectangular or circular. For this purpose, 12 square plates (1.5 m x 1.5 m and 4.0 or 6.0 cm in thickness) models having different opening sizes, shapes, and locations were casted, treated, and tested under the effect of concentrated load. Also 2 models without openings were tested under the same conditions for comparison. In this work each plate was rested on four corner supports and loaded in increments up to failure. Deflections, strains and cracks propagation were recorded after each increment, also the first cracking loads and the ultimate failure loads were registered. It was found that the thicker slabs are much better than those with small thickness. The circular openings are most suitable than circular ones, and no need to take any precautions regarding the thickness or reinforcement if the opening diameters or side length is lass than or equal to one tenth of the slab side length.

تعتبر البلاطات اللاكمرية ذات أهمية كبيرة واستخدامات عديدة ويرجع ذلك إلى سهولة تنفيذها ، ورخص تنفيذها نسبيا، وكذلك إتاحة الفراغ المناسب لتمديدات التكييف والصحى بدون عوائق من الكمرات الساقطة . وهذه التمديدات قد تحتاج فى بعض الأحيان إلى وجود فتحات لتمريرها بين الأدوار المختلفة. و نظرا لصعوبة التحليل النظرى للبلاطات المسلحة اللاكمرية وخاصة فى حالة وجود فتحات فى هذه البلاطة تظل الاختبارات المعملية طريقة فعالة لدراسة سلوك هذه البلاطات كما أنها فى نفس الوقت تحقق وتدقق نتائج التحليل النظرى وتعطيه قوة ومصداقية فى إمكانية الاعتماد عليه مستقبلا دون إجراء اختبارات معملية. ولدراسة سلوك البلاطات اللاكمرية ذات الفتحات فقد تم اجراء دراسة عملية لدراسة سلوك هذه البلاطات الخرسانية المسلحة اللاكمرية المحتوية على فتحات مربعة أو دائرية تحت تأثير الأحمال المركزة. ولهذا الغرض تم اعداد ١٢ بلاطة مسلحة لا كمرية ذات ابعاد ثابتة وولكن لها فتحات ذات ذات أبعاد مختلفة وفى مواضع مختلفة من البلاطة ولها شكل دائرى أو مربع. كما تم إعداد عدد ٢ بلاطة بدون فتحات تحت نفس الظروف وذلك لعمل دراسة مقارنة. وفى هذه الدراسة تم وضع البلاطات على أربع ركائز فى الأركان وتم تحميلها بأحمال مركزة تزداد تدريجيا حتى الانهيار. و قد تم تسجيل الترخيم والانفعال و تزايد ظهور الشروخ خلال مراحل التحميل المختلفة بالاضافة إلى حمل التشريخ الابتدائى والحمل الأقصى لكل بلاطة. وبمقارنة حمل التشريخ والحمل الأقصى فى كل حالة أمكن دراسة تأثير وجود الفتحات وأبعادها وأماكنها على مقاومة البلاطة للأحمال المؤثرة عليها وبذلك يمكن تحديد المكان المناسب وأبعاد الفتحات المناسبة والتى لا تؤثر تأثيرا كبيرا على مقاومة البلاطات اللاكمرية لمقاومة الأحمال.

Keywords: Reinforced concrete, Flat slabs, Opening, Concentrated loads, Deflection

1. Introduction

Flat slab systems of construction is widely used in office buildings, institutional structures, apartment buildings, and hotels because of their simplicity, construction time saving, adequacy for placing utilities of air conditioning and plumbing, and flexibility of using the spaces without any obstacles.

Openings in flat slabs of buildings are required for different purposes like installation of air conditioning ducts, plumbing, and other services.

The purpose of this study is to investigate the effect of openings with different shape, size, and location on the behavior of flat plates resting on four corner supports under the application of concentrated loads.

2. Experimental program

The tested plates for the present study are classified into four groups. Each group defined by four characters; the first one is the letter C which indicates slabs with central opening, the letter E indicates slabs with eccentric

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opening, and letter S for solid plate without any openings. The second character is a number representing the side length, or the length of diameter, of the opening. The third one represents the shape of the opening, Î for square openings and O for circular openings, and X for solid plate. The last character is a number representing the plate thickness. All plate models have a side length of 150 cm.

2.1. Models of group I

This group includes two solid plates 6 cm and 4 cm thickness without openings, SOX6 and SOX4, respectively.

2.2. Models of group II

This group includes six plates with central square opening of 20 cm, 30 cm, and 50 cm side length with 6 cm and 4 cm thickness C2Î6, C3Î6, C5Î6, C2Î4, C3Î4 and C5Î4, respectively.

2.3. Models of group III

This group includes two plates having central circular openings of 50 cm diameter with 6 cm and 4 cm thickness C5O6, C5O4, respectively.

2.4. Model of group IV

This group includes four plates having eccentric (Center of opening coincides with the center of the slab corner) square openings of 30 cm and 50 cm side length with 6 cm and 4 cm thickness E3Î6, E5Î6, E3Î4 and E5Î4, receptively.

3. Properties of the used materials

3.1. Aggregates

(a) Gravel: well graded natural gravel of maximum nominal size 10 mm was used for casting all specimens. The gravel was washed and then dried at room temperature.

(b) Sand: well graded, clean, free of organic matters and any other impurities sand was used.

3. 2. Cement

Ordinary Portland cement complied with E.S.S.373 requirements was used.

3. 3. Steel reinforcement

Plain bars of normal mild steel (St.37) were used in all models. The yield strength f_y is equal to 2400 kg/cm^2.

3. 4. Water

Clean potable water was used in all mixes, to give water cement ratio w/c = 0.5.

4. Mixes proportions

The concrete mixes used in casting all specimens had the mix proportion (by weight) shown in table 1.

Materials used to produce one cubic meter of concrete are given in table 2.

5. Casting forms and test rig

The R. C. slabs were cast in wooden forms consists of square beds made of plywood and square frames each of 150 cm clear side length with 6 cm or 4 cm depth. Standard steel sections frame was used as a test rig.

Table 1
Concrete mix proportions by weight

Cement	Sand	Gravel	W/C
1.0	2.0	4.0	0.50

Table 2
Materials used for 1.0 m^3

Cement	Sand	Gravel	Water
350 kg	700 kg	1400 kg	175 Lit.

6. Casting and curing of specimens

A mechanical concrete mixer of 0.05 m^3 capacity was used to obtain the concrete mixes for all models. The plywood forms were cleaned and washed. Then the steel reinforcement meshes put into its position. The concrete was compacted manually using a standard compactor rod, then the models surfaces were finished using a straight piece of wood. Standard cubes were cast in them same time with plat models. After 24 hours models were cured keeping them wet for 14 days.

7. Dimensions and reinforcement of tested plates

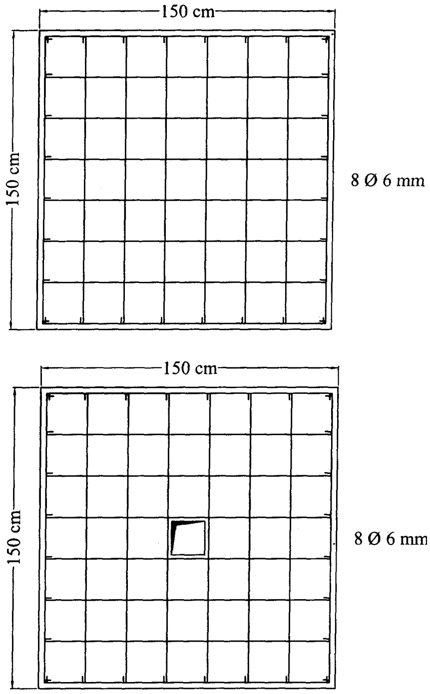
Eight plain bars of 6 mm diameter in bottom in each direction were used in all tested slabs, either for 6 cm or 4 cm thickness. The typical dimensions and reinforcement arrangement of the four tested groups are shown in figs. 1 to 5.

8. Testing procedure

All plate models were tested using the steel frame supported on four corner supports; each was a steel plate 5 x 5 cm. A compressible material of 1 cm thickness was placed between the reinforced concrete plate bottom surface and the supports to prevent any stress concentration and to distribute each reaction force uniformly on the supporting area. Each plate model was loaded up to failure using the steel frame applying the load by a hydraulic jack. The load increments achieved by increasing hydraulic jack compression, each load increment was 250 kg for the 6 cm thickness plate models and 125 kg for the 4 cm thickness plate models. After each load increment, the strains, deflections, first cracking loads and failure loads were recorded, also cracks propagation were marked.

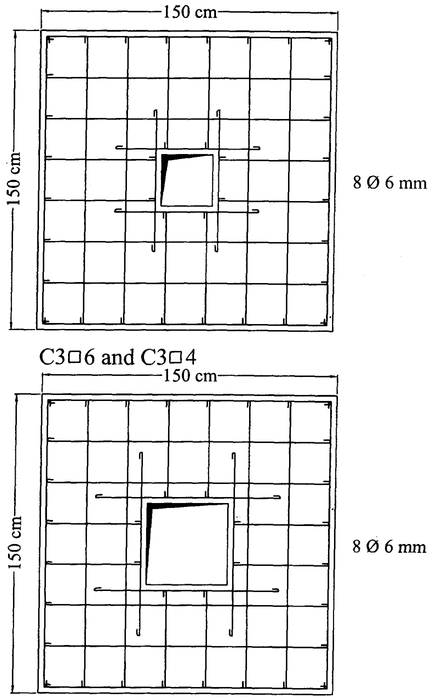
9. Discussion of the test results

The test results of the fourteen plate models are presented and discussed in the following points:



C2□6 and C2□4

Fig. 1. Typical dimensions and reinforcement arrangement for groups 1 and 2a.



C5□6 and C5□4

Fig. 2. Typical dimensions and reinforcement arrangement for groups 2b.

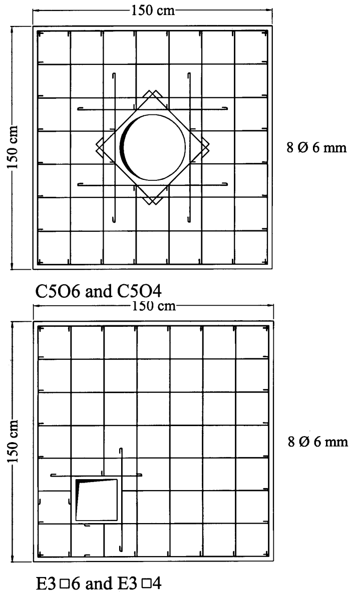


Fig. 3. Typical dimensions and reinforcement arrangement for groups 3 and 4a.

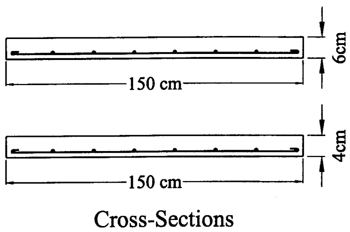


Fig. 4. Typical dimensions and reinforcement arrangement used in the two used thicknesses.

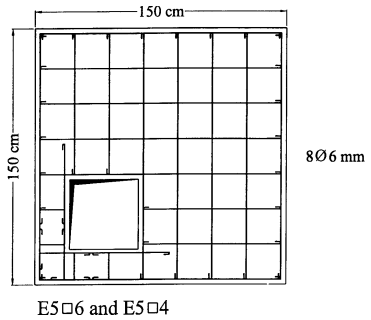


Fig. 5. Typical dimensions and reinforcement arrangement for groups 4b.

9.1. Load deflection relationships

At the chosen eight points, the deflection values were recorded, six points laying along the center line of slab model, point 1 and point 6 at the opposite edges to check uniformity of loading, the other points laying along the diagonal line. We find these points are enough to represent the deflection of the tested models [fig. 6]. The deflection values were recorded before and after the application of each load increment and up to failure. To show the deflection behavior the fourteen plate models were divided into four groups.

9.2. Comparison of different groups deflections

Figs. 7 through 14 show comparison between the deflection values recorded for slab models of groups 1, 2 and 3 without and with central opening at different points in the slab. This comparison indicates that the deflection values recorded at the same point for different slabs gives greater values for slab with opening. In other words, the bigger the opening dimensions the greater the deflection values. It can also be noted that slabs with circular opening (group 3) of diameters equal to the side length of square openings indicates lower values of deflection at the same load intensity.

Figs. 15 through 22 show comparison between the deflection values for slab models of groups 1 and 4 without and with eccentric openings, respectively, at different points in the slab. The deflection values recorded at the required points in slabs E5î6 and E5î4, were greater than those recorded at the corresponding points for E3î6 and E3î4, respectively. Deflection of solid slabs models SOX6 and SOX4 indicated lower values compared with those of group 4.

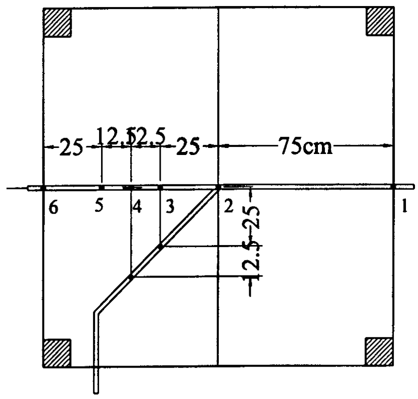


Fig. 6. Arrangement of dial gauges.

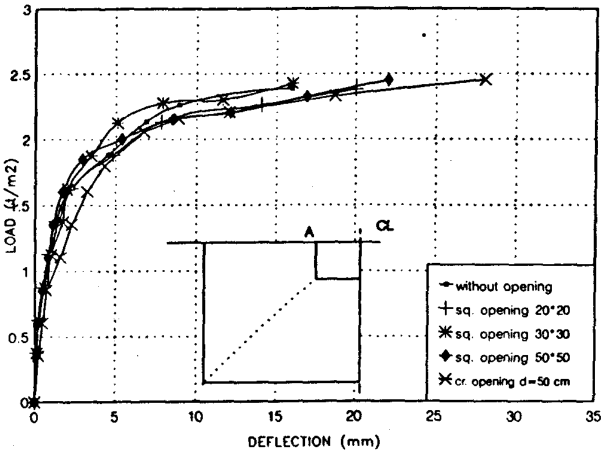


Fig. 7. Experimental load-deflection relationship for 6 cm thickness plate with different central opening (point A).

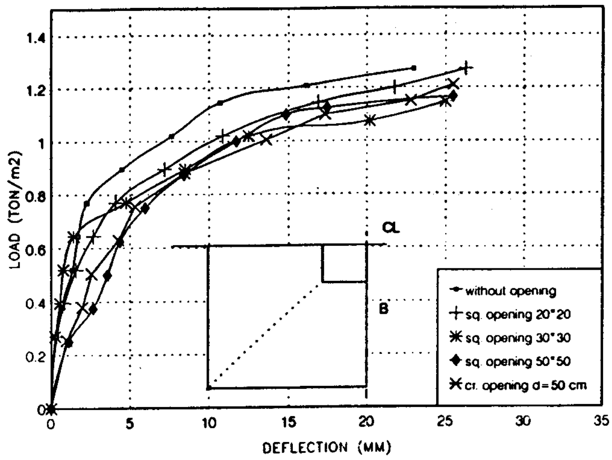


Fig. 10. Experimental load-deflection relationship for 4 cm thickness plate with different central opening (point B).

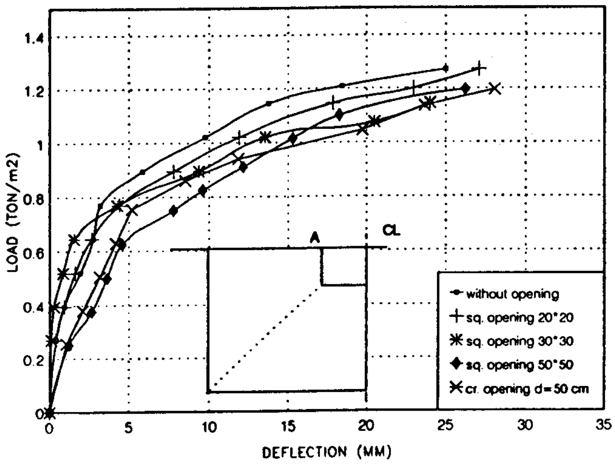


Fig. 8. Experimental load-deflection relationship for 4 cm thickness plate with different central opening (point A).

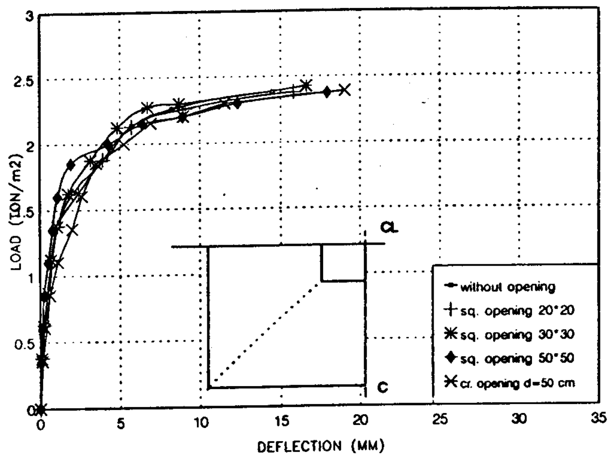


Fig. 11. Experimental load-deflection relationship for 6 cm thickness plate with different central opening (point C).

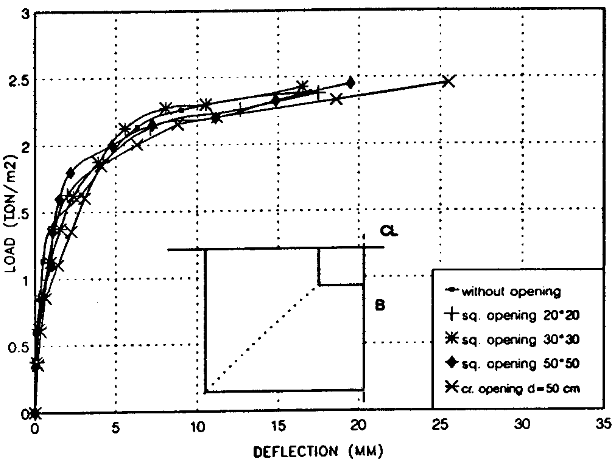


Fig. 9. Experimental load-deflection relationship for 6 cm thickness plate with different central opening (point B).

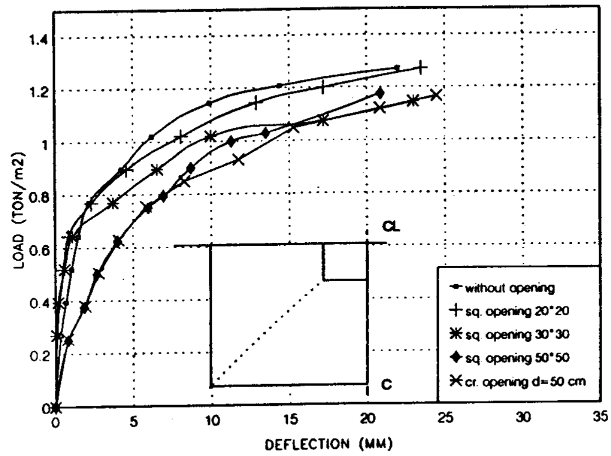


Fig. 12. Experimental load-deflection relationship for 4 cm thickness plate with different central opening (point C).

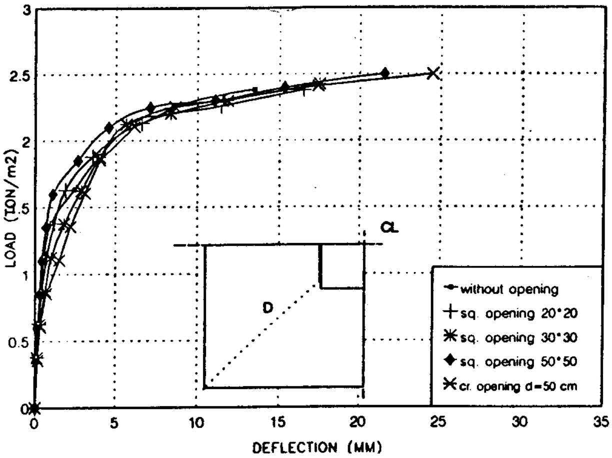


Fig. 13. Experimental load-deflection relationship for 6 cm thickness plate with different central opening (point D).

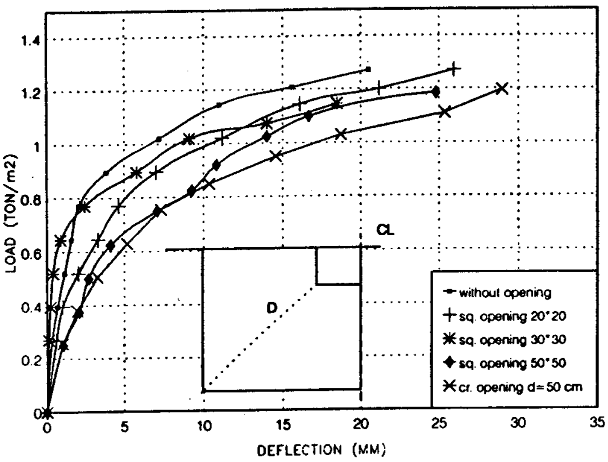


Fig. 14. Experimental load-deflection relationship for 4 cm thickness plate with different central opening (point D).

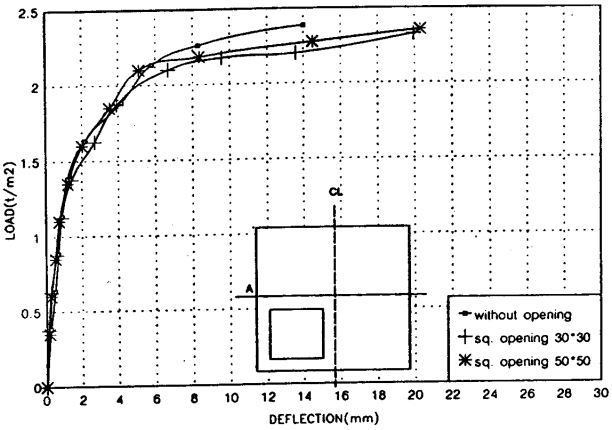


Fig. 15. Experimental load-deflection relationship for 6 cm thickness plate with different central opening (point A).

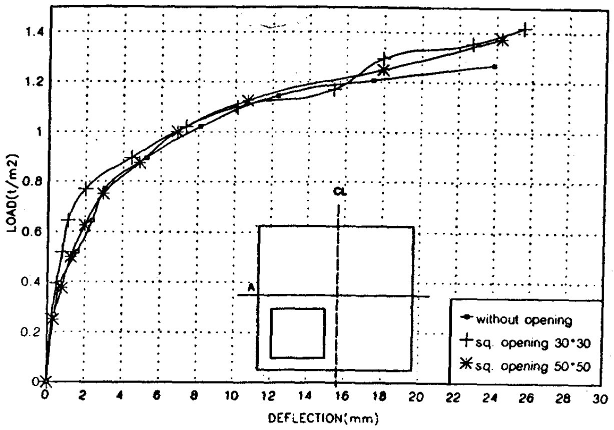


Fig. 16. Experimental load-deflection relationship for 4 cm thickness plate with different central opening (point A).

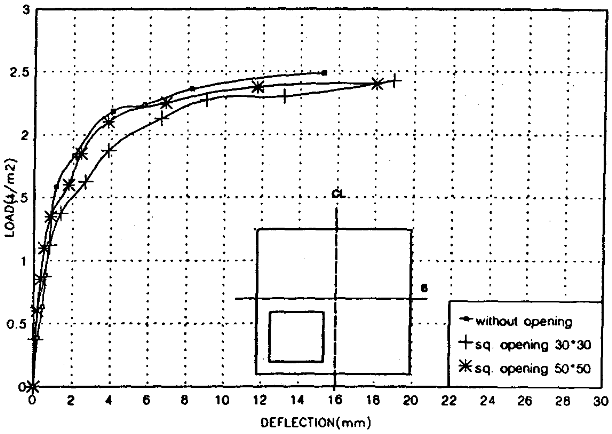


Fig. 17. Experimental load-deflection relationship for 6 cm thickness plate with different central opening (point B).

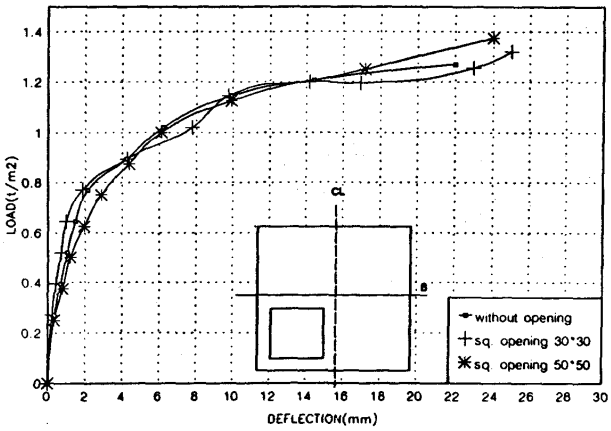


Fig. 18. Experimental load-deflection relationship for 4 cm thickness plate with different central opening (point B).

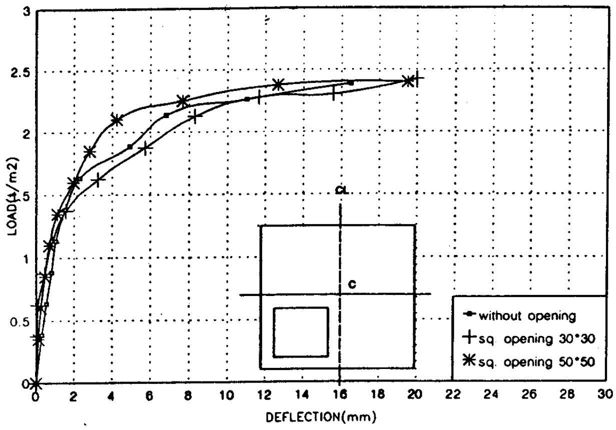


Fig. 19. Experimental load-deflection relationship for 6 cm thickness plate with different central opening (point C).

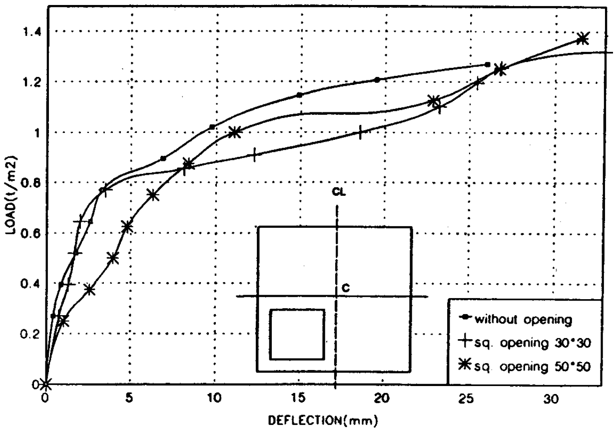


Fig. 20. Experimental load-deflection relationship for 4 cm thickness plate with different central opening (point C).

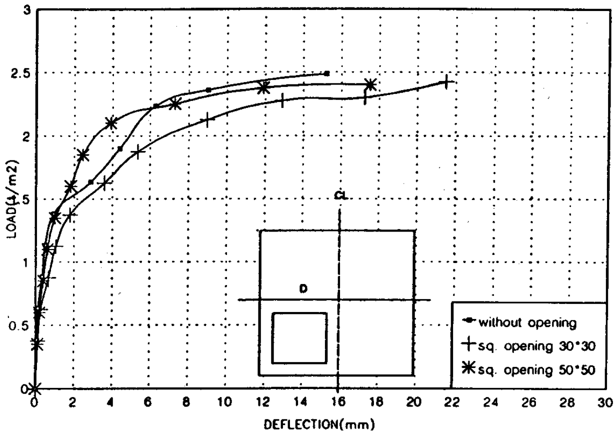


Fig. 21. Experimental load-deflection relationship for 6 cm thickness plate with different central opening (point D).

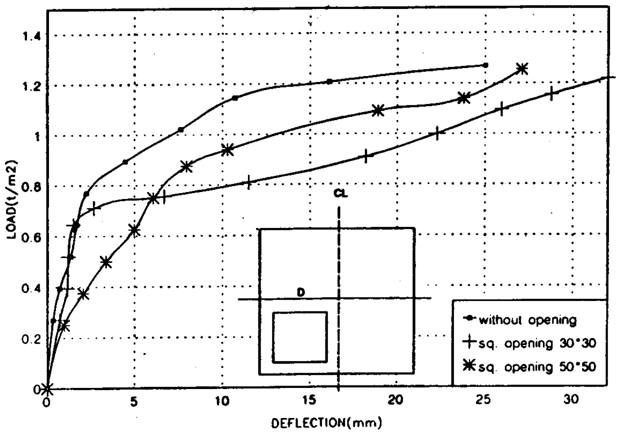


Fig. 22. Experimental load-deflection relationship for 4 cm thickness plate with different central opening (point D).

9.3. Load – strain relationships

Figs. 23 through 26 show the relations between load and maximum strains for the tested slabs. The maximum strain values for group 1 were recorded at central point (point 2). For group 2 the maximum strains recorded at the corners of the square central openings, while for group 3 including slabs with circular central openings, the maximum recorded strains were at the circumference of the openings.

For group 4 of square eccentric openings, the maximum strain values recorded at the corners nearest to the center of the slabs. The figures show that the bigger the openings sizes the greater the maximum strains. It can be noted that the strains recorded for group 3 is more uniform and having lower values than those of group 2 having square central openings with side length equal to the diameter of the circular openings. From figures, one can notice that the maximum strains for group 4 with eccentric square openings were greater than both those for solid slabs of group 1 and those for group 2 with corresponding central square opening of the same dimensions.

9.4. Cracking and failure loads

The initial cracking loads for the tested slabs were recorded and the positions of the first cracks along the bottom surface were marked. As the applied load was increased more cracks appeared. After each load increment the new additional cracks were marked and their corresponding loads were recorded. This procedure continued up to failure.

9.5. Cracking and failure loads for group 1

Figs. 27 and 28 show the crack patterns of this group. These figures indicate that, the cracks started at middle third of the bottom surface in the two reinforcement directions and increased towards the slab edges. The cracks were observed first at a total load of (P_{C6}=1385 kg) for slab SOX6 and at a total load of (P_{C4} =770 kg) for slab SOX4. The first observed cracks were in a direction parallel to that of the top steel reinforcement bars, and after a while under the same load cracks were observed in a perpendicular direction parallel to that of the bottom steel reinforcement bars.

The failure loads for this group were (P_{F6} =2850 kg) and (P_{F4}=1375) kg for slabs SOX6 and SOX4, respectively. The last cracks appeared just before failure, were the diagonal cracks near the corner supports.

The loads for the next groups will be represented as a ratio of the loads of slabs of group 1 of the same thickness, for example cracking loads will be divided by the cracking load of SOX6 or SOX4 according to the thickness. Also the failure loads will be divided by the failure loads of SOX6 or SOX4 according to the thickness.

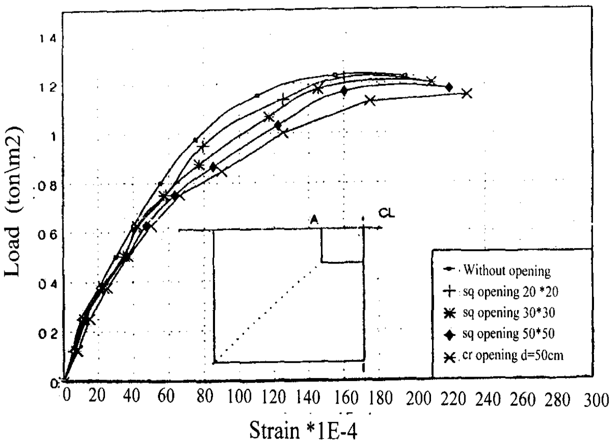


Fig. 23. Experimental load-deflection relationship for 6 cm thickness plate with different central opening (point A).

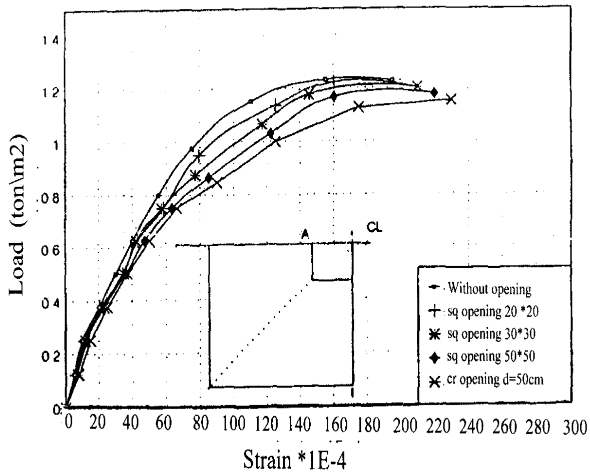


Fig. 24. Experimental load-deflection relationship for 4 cm thickness plate with different central opening (point A).

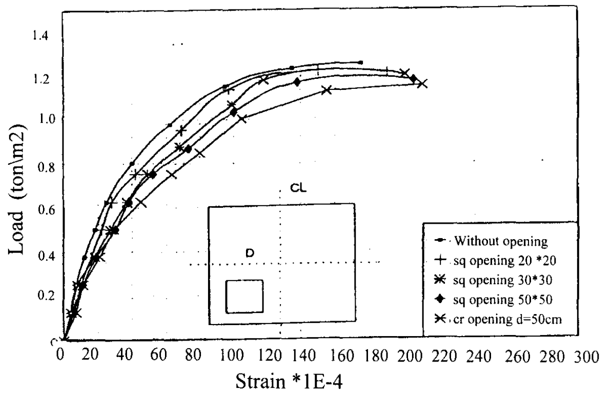


Fig. 25. Experimental load-deflection relationship for 6 cm thickness plate with different central opening.

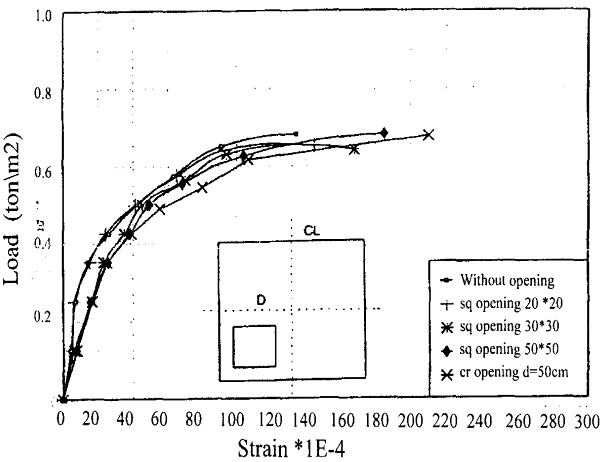


Fig. 26. Experimental load-deflection relationship for 4 cm thickness plate with different central opening.

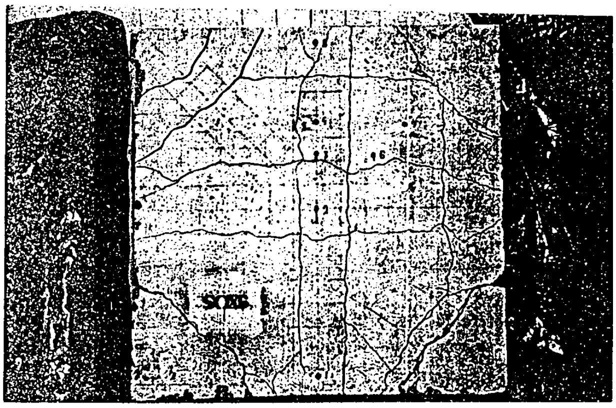


Fig. 27. The crack patten of slab (SOX6).

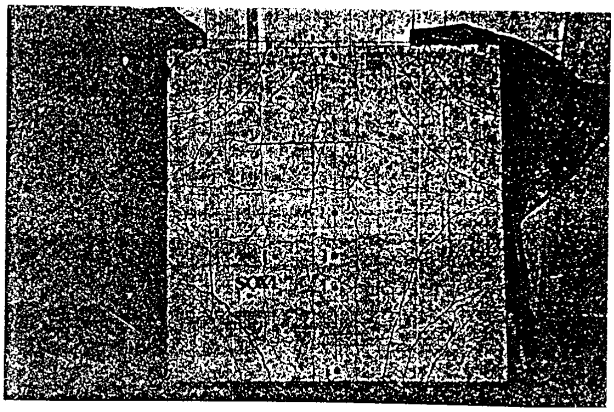


Fig. 28. The crack patten of slab (SOX4).

9.6. Cracking and failure loads for group 2

Figs. 29 through 34 show the cracks patterns of group 2 with central square openings. These figures indicate that, the initial cracks started at the corner of the square opening and increasing parallel to the direction of steel reinforcement bars towards the slab edges.

The first observed cracks were at a relative loads of (0.94, 0.90 and 0.87) of P_{C6} for slabs C2î6, C3î6 and C5î6 respectively, and (0.93, 0.88 and 0.78) of P_{C4} for slabs C2î4, C3î4 and C5î4, respectively.

The first observed cracks were growing similar to those of group 1. The failure load for this group were (0.96, 0.89 and 0.82) of P_{F6} for slabs C2î6, C3î6 and C5î6, respectively, and (1.0, 0.92 and 0.90) of P_{F4} for slab C2î4, C3î4 and C5î4, respectively. The diagonal cracks near the corner supports were the last observed cracks just before failure.

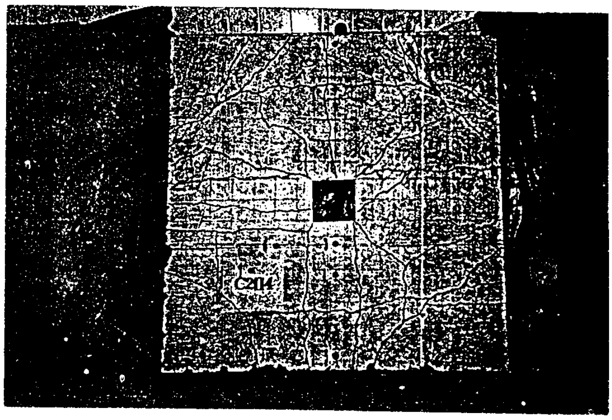


Fig. 29. The crack patten of slab (C2î6).

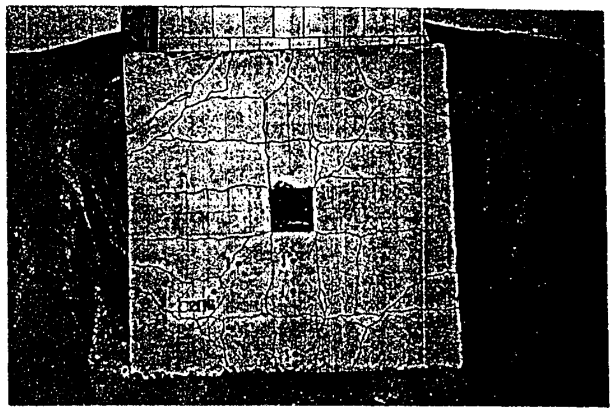


Fig. 30. The crack patten of slab (C2î4).

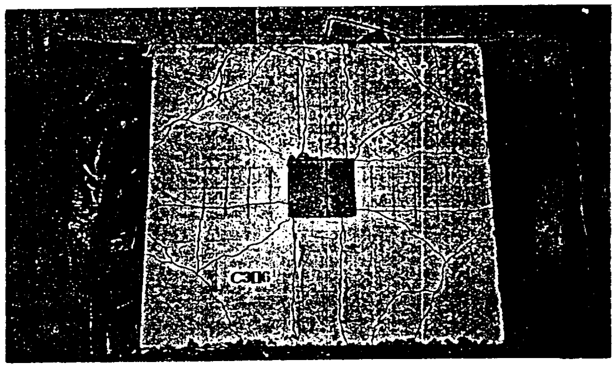


Fig. 31. The crack patten of slab (C3î6).

9.7. Cracking and failure loads for group 3

Figs. 35 and 36 show the cracks patterns of this group. From these figures, it can be noted that, the initial cracks started at the edge of the circular opening taking the direction of the diameter for short distance and then growing in a direction parallel to that of the steel reinforcement bars towards the slab edges. The first observed cracks were at a total load of (0.87 P_{C6}), for slab C5O6, and (0.92 P_{C4}) for slab C5O4.

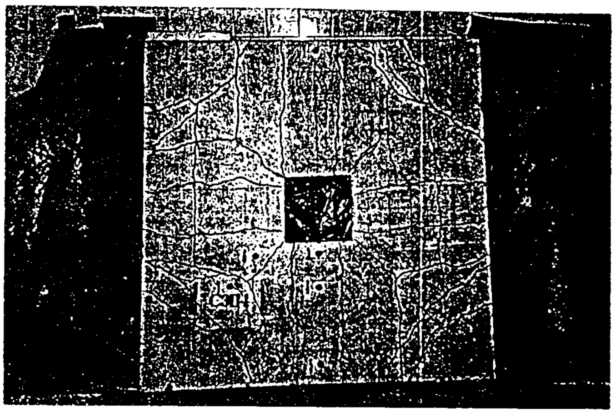


Fig. 32. The crack patten of slab (C3Î4).

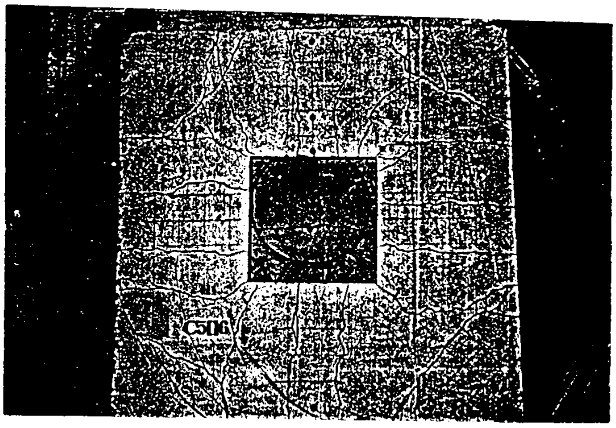


Fig. 33. The crack patten of slab (C5Î5).

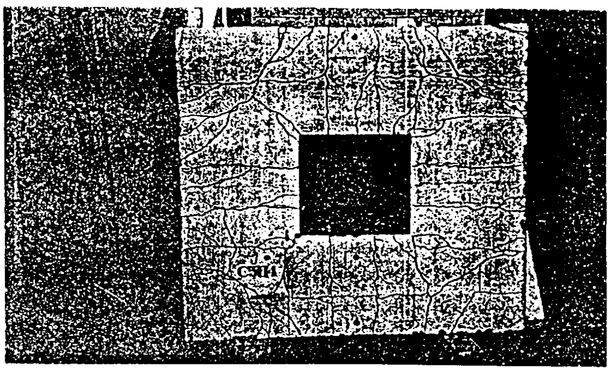


Fig. 34. The crack patten of slab (C5Î4).

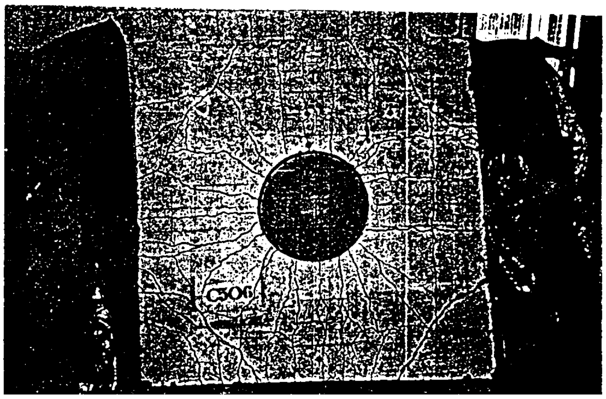


Fig. 35. The crack patten of slab (C5Î6).

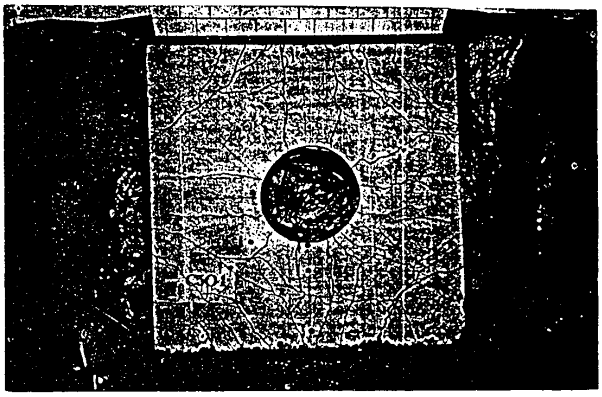


Fig. 36. The crack patten of slab (C5Î4).

The first observed cracks behave identically as those of group 1. The failure loads for this group were (0.86 P_{F6}), and (0.98 P_{F4}) for slabs C5O6 and C5O4 respectively. The diagonal cracks near the four corner supports were observed just before failure.

9.8. Cracking and failure loads for group 4

Figs. 37 through 40 show the cracking patterns of this group. These figures indicate that, the initial cracks started at the corner of the opening which is nearest to the center of the slab. Other cracks started at the sides of the opening and extended perpendicular to these sides. Another type of cracks parallel to previous ones appeared almost at the center line of the slabs at the same initial cracking loads. The first observed cracks were at total load of (0.83 P_{C6}) and (0.79 P_{C6}) kg for slabs E3Î6 and E5Î6, respectively, and (0.87 P_{C4}) kg, and (0.81 P_{C4}) kg for slabs E3ȋ4 and E5ȋ4, respectively. The first observed cracks were identically behaved as those of group 1.

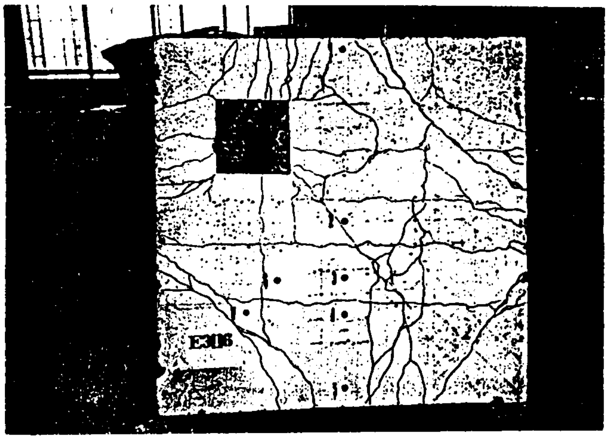


Fig. 37. The crack patten of slab (E3ȋ6).

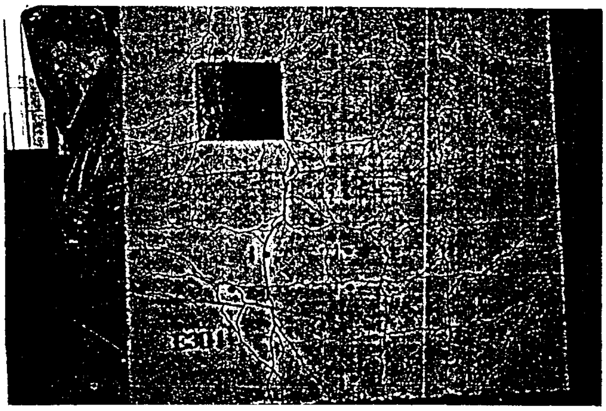


Fig. 38. The crack patten of slab (E3ȋ4).

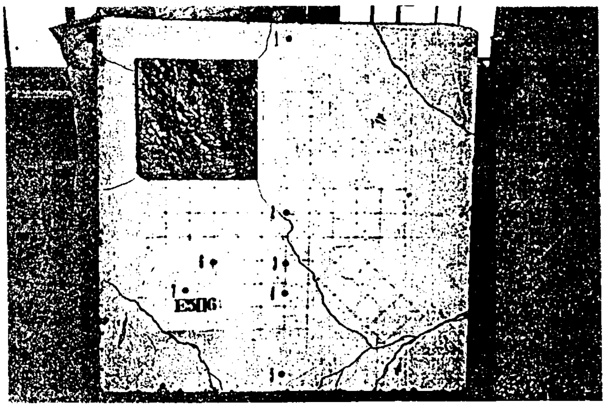


Fig. 39. The crack patten of slab (E5ȋ6).

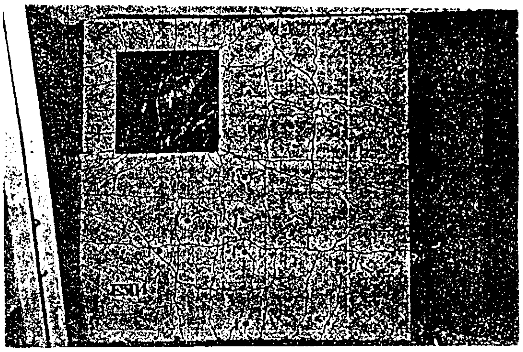


Fig.40. The crack patten of slab (E5ȋ4).

The failure loads for this group were (0.88 P_{F6}) and (0.82 P_{F6}) for slabs E3ȋ6 and E5ȋ6 respectively, and (0.92 P_{F4}), (0.87 P_{F4}) for slabs E3ȋ4 and E5ȋ4, respectively. The diagonal cracks at failure appears around the three corner supports away from the opening, while at the corner support near the opening the diagonal cracks grow as shown in figure and appear in the zones between both edges of opening and slab.

10. Conclusions

From this experimental work and its results the following conclusions can be drawn:

1. The presence of openings in flat slabs decreases the strength and rigidity of the flat slabs depending on the sizes, shapes, and locations of these openings.
2. The bigger the dimension of the opening, the higher the deflection values at any point in the slab for the same loading.
3. The deflection values of the slabs with square openings are about 125% higher than those of slabs with circular openings having diameter equal to the square opening side length.
4. The deflection increases at the positions which are close to the openings, and decreases in the positions which are far from openings and continue in decreasing gradually.
5. The carrying capacities of flat slabs with eccentric openings (at the center of the quarter) decreased to 90% of those with central openings of the same shapes and sizes.
6. The maximum strains for slabs with openings occur at both, the corners of square opening and the edge of circular opening

nearest to the center of the slab, but slabs with circular openings have lower values and more uniform strain distribution than those of square openings.

7. Existence of openings in flat slabs of small thicknesses affects their behavior more than those of big thicknesses. In other words, the thinner the slab thickness the more deflections and strains due to opening existence at the same loading stages.

8. The deviations in some experimental results for 4 cm thickness slab can be regarded to the membrane action or to the sensitivity of small thickness slabs to casting, curing or loading conditions. These deviations vanished in slab models with 6 cm thickness.

9. The most suitable shape of an opening in the slab is the circular shape and the most preferable location is away from the corner supports.

10. There is no need to take any precautions regarding the slab thickness or reinforcement if the diameter (or side length) of the opening is about one tenth of the slab side length.

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