Effect of Openings on the Performance of Continuous RC One-Way Slabs

Nameer M. Jawad Al-Quraishy
Department of Civil Engineering, Collage of Engineering, University of Basrah, Basrah, Iraq
engpg.nameer.jawad@uobasrah.edu.iq (corresponding author)

Thaer M. Saeed Alrudaini
Department of Civil Engineering, Collage of Engineering, University of Basrah, Basrah, Iraq
thaer.abdulhameed@uobasrah.edu.iq

Yousif J. Lafta
Department of Civil Engineering, Collage of Engineering, University of Basrah, Basrah, Iraq
yousif.lafta@uobasrah.edu.iq

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ABSTRACT

Nowadays, slab openings have become necessary for service purposes in most new and old constructions, therefore, their effect on the slab strength should be extensively investigated. This paper explores the effect of such openings on the performance of a one-way continuous Reinforced Concrete (RC) slab. Fourteen slabs with different opening categories were cast. The main parameters studied in this research were the opening size, opening location, and slab thickness. The study focused on two span slabs, including openings with and without the proposed diagonal reinforcement at the corners. All slabs had identical spans and widths whereas two thicknesses were used. Openings of varying sizes were introduced at different locations within the spans. The results indicate a significant reduction in load capacity and ductility for the slabs with openings. The largest reduction occurred when the largest opening was placed near the mid-support, resulting in a 21.3% decrease in load capacity. Conversely, the smallest reduction was observed in the slab with the same large opening but with additional reinforcement, resulting in only a 1.74% decrease in load capacity.

Keywords-continuous slab; opening; reinforced concrete; crack load

I. INTRODUCTION

Building requirements for varied and complex services related to the mechanical, electrical, and plumbing works of modern buildings have made slab openings necessary during a building's construction or after its completion. Therefore, it is essential to study these openings and their effect on the structure and slabs in terms of ultimate load strength, flexural, displacement, and shear strength. Many researchers have investigated this topic from different perspectives. In [1], the experimental results of the punching shear strength of a two-way slab that demonstrated a reduction in punching shear strength up to 60 % depending on the opening size and location were presented. Authors in [2] studied the effect of the number and opening patterns on the punching shear strength of flat slabs. In [3], a reduction of 18.2 % was found in two-way slabs in the presence of openings. In [4], a 50% reduction in a one-way plate was documented due to the presence of openings. Authors in [5] showed that a one-way slab with an opening size of less than 5 % of the slab area resulted in a slab capacity drop of less than 20%. On the other hand, several studies have considered strengthening schemes to compensate for the reduction in slab capacity due to the presence of slab openings with a main focus on using Carbon Fiber-Reinforced Polymer (CFRP) materials [6, 7]. In [8], the impact of openings in large-scale RC slabs and the use of mechanically reinforced carbon fiber polymers to restore these slabs' capacity decrease were studied. The openings' influence on the ultimate capacity varied between 30% and 70%. Authors in [9] studied the behavior of flat slabs with openings adjacent to columns. Both analytical and experimental investigations were conducted considering seven large-scale flat plate slabs. Their dimensions were 1700 mm × 1700 mm × 150 mm. One slab without an opening was regarded as the reference slab and the rest were divided into two groups. The first group contained three slabs with openings in front of the column face, while the second contained three slabs with openings at the column corner. The test results revealed that the location of the opening and its dimensions had a significant effect on these slabs' capacity. In [10], an experimental study on self-compacting RC slabs with openings, strengthened with laminated carbon fibers and steel fibers was introduced. Eight slabs with openings were tested.

The openings resulted in a load capacity decrease by about 30%, which was fully restored by using the CFRP strengthening technique. Authors in [11] tested six one-way slabs containing an opening adjacent to a central patch load in addition to one control slab without any openings. They investigated the effect of the opening on flexural strength and produced a strengthening method using near-surface-mounted steel bars and externally bonded CFRP on the tension side. The results displayed that the strengthening method totally restored the strength of the slabs. In [12], eight tests were carried out to investigate the strength of RC slabs with and without cut-out openings. The load and deflection capacity of the slabs were reduced by the cut-out openings. The CFRP strengthening enhanced the slab with a cut-out opening by up to 121% and the slab without a cut-out opening by up to 57%. In [13], nine slabs with openings and one without (control sample) were investigated. The openings reduced the maximum resistance of the slabs and increased their deflection. The use of CFRP sheets restored the resistance and decreased these slabs' deflection. Authors in [14] studied the strengthening of two-way RC slabs with a central opening. Six RC slabs with openings were tested along with one slab without an opening. The results disclosed that the CFRP strengthening method could increase the ultimate strength and flexural stiffness, which were affected by the presence of an opening. Moreover, it was shown that embedding extra steel bars around the opening, as proposed in [15], may not enhance the slab load-carrying capacity compared to the value of the continuous slab. The results also exhibited that the deflection increased because of the cut-out opening and that the strengthening methods had not restored that deflection. Authors in [16] studied the flexural strength recovery of RC one-way slabs with cut-outs using NSM-SHCC plates. Ten specimens were tested. It was demonstrated that the opening in the slabs caused a significant reduction in their strength and ductility. This reduction was compensated by developing a strengthening method, applying Strain-Hardening Cementitious Composites (SHCC) in both tension and compression zones. Authors in [17] presented an experimental and numerical investigation on the punching behavior of two-way RC slabs with different opening locations and sizes strengthened with a CFRP strip. The considered variables were the size and location of the opening. The results exhibited a high negative effect on the slab strength. A strengthening technique of fan-type anchors and CFRP was employed to retrieve about 50% of the lost strength of the slabs. In [18], 10 RC beams were examined to investigate the impact of the vertical positioning and size of the opening on the bending and shear performance of those beams. The results showed that openings of a depth greater than 0.4 d affected the beam strength and led to earlier cracks. At the same time, the failure mode remained the same except for the opening with a depth more than 0.5 d, where the failure changed to shear failure. When the hole was above the centroid of the cross-section, the beam recorded lower deflection due to the absence of plasticity. Authors in [19] studied the behavior of RC beams with vertically penetrated holes across the cross-sectional depth. Five specimens with vertical openings were examined, with one being used as the control beam. It was found that the vertical openings reduced the ultimate load capacity and induced the deflection.

In the current study, the behavior of one-way continuous slabs containing small openings with different sizes and locations was experimentally investigated. Moreover, the openings' impact on continuous one-way slabs consisting of two spans was examined, whereas, most previous research papers have solely considered the effect of the openings in single one-way and two-way slabs. Fourteen one-way continuous RC slabs were cast. Two slabs were used as the control slabs and the parametric effect of twelve other slabs with openings was explored. The considered parameters were the sizes and locations of the square and rectangular openings, as well as two different slab thicknesses.

II. EXPERIMENTAL WORK PROGRAM

A. *Test Specimens*

To investigate the behavior of continuous one-way slabs with openings, a total of 14 specimens were prepared and tested. These specimens were divided into two groups. The first group consisted of 10 specimens with a thickness of 120 mm. One of these specimens was cast without any openings (control sample), while the other nine specimens had openings of different sizes and locations. The second group consisted of four specimens with a thickness of 150 mm. One of these slabs was cast without any openings, acting as the reference slab and the three others had openings of different sizes and locations. Concrete of 35 MPa strength was used with steel reinforcements of 10 mm diameter and 180 mm c/c spacing for all specimens, as depicted in Figure 1.

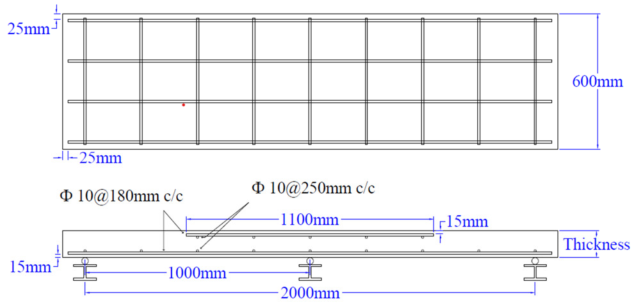

Fig. 1. Reinforcement details of slab.

B. *Opening Details*

The length and width of all slabs were kept constant at 2200 mm and 600 mm, respectively. Slab thicknesses were 120 mm and 150 mm for group 1 and group 2, respectively. The slab parameters are defined in Table I. The opening dimensions of the S1, S2, and S3 specimens were 160 mm × 160 mm but the locations of the openings varied. The openings of S1 were closer to the middle support, the openings of S2 were in the middle of each span, and the openings of S3 were far from the middle support.

Both S4 and S5 had an opening of 100 mm × 100 mm, one close to and the other far from the middle support. S6 and S7 were similar to S1 and S2, but with additional diagonal reinforcements at the corners of the openings. The openings of S8 and S9 had dimensions of 220 mm × 100 mm. S8 had an opening in both spans, but S9 had an opening in one span to evaluate the effect of a slab opening on an adjacent one. Finally, S10, S11, and S12 were similar to S1, S8, and S9 sequentially, but the thickness of the slabs was 150 mm instead of the required 120 mm. The details of the considered slabs are illustrated in Figure 2.

TABLE I. SPECIMEN DETAILS

Slab No.	Slab thickness (mm)	Opening dimensions (mm × mm)	Opening position	Additional reinforcement	Opening distance from the middle support (mm)
C1	120	- -	-	No	-
S1	120	160 × 160	Two Spans	No	50
S2	120	160 × 160	Two Spans	No	300
S3	120	160 × 160	Two Spans	No	500
S4	120	100 × 100	Two Spans	No	50
S5	120	100 × 100	Two Spans	No	500
S6	120	160 × 160	Two Spans	Yes	50
S7	120	160 × 160	Two Spans	Yes	300
S8	120	220 × 100	Two Spans	No	500
S9	120	220 × 100	One Span	No	500
C2	150	- -	-	No	-
S10	150	160 × 160	Two Spans	No	50
S11	150	220 × 100	Two Spans	No	500
S12	150	220 × 100	One Span	No	500

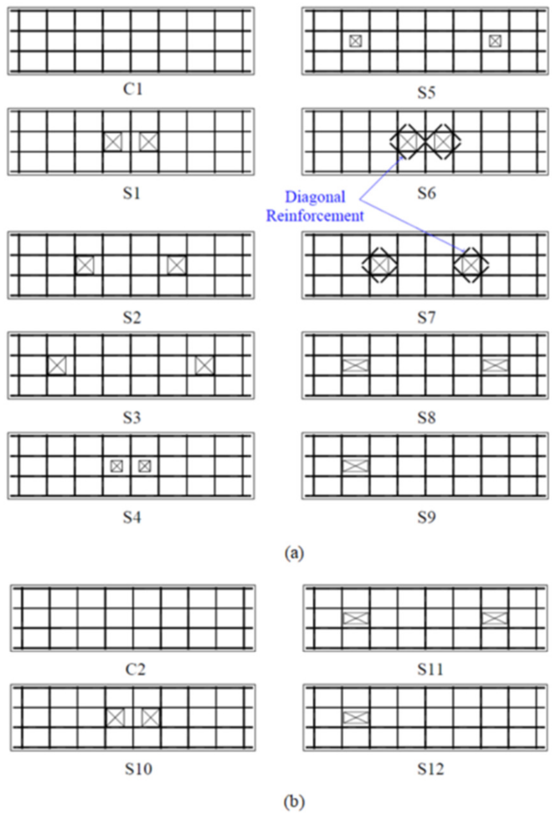

Fig. 2. (a) Group 1-thickness: 120 mm, (b) group 2-thickness: 150 mm.

TABLE II. CONCRETE PROPORTIONING

Water (kg)	Cement (kg)	Coarse aggregate (kg)	Fine aggregate (kg)	Super plasticizer (kg)
158	395	1110	716	1.58

C. *Materials*

In this research, ordinary Portland cement was used, which complies with Iraqi specifications [20]. Both the fine and coarse aggregates utilized were brought from Al-Zubair District in Basra. They complied with the findings of [21, 22] and were compared with those of [23]. Ordinary potable water was used to cast and cure the specimens. A new generation of super plasticizing admixture, including high range plasticizer of Turkish origin, called PLATINUM RMC 2255 was used. Steel bars with 10 mm diameter were utilized for both layers (upper and lower). The yield strength of steel was 512 N/mm^2 and the ultimate strength was 699 N/mm^2. The concrete mix design was conducted according to [24]. Table II shows the proportions of concrete per m^3. All specimens were cast and tested in the construction material laboratory of the Department of Civil Engineering, College of Engineering, University of Basra.

Figure 3 portrays the test setup in which the load was symmetrically distributed into two line loads. Each line load was applied at the center of each span, and two displacement gauges were installed under each load.

III. EXPERIMENTAL RESULTS AND DISCUSSION

All specimens were tested according to the scheme shown in Figure 3. Figure 4 demonstrates these specimens after failure.

A. *Effect on Strength*

The load-deformation performance of the slabs was examined and their yield load, ultimate load, and corresponding deformations were recorded. Table III outlines the test results.

B. *Effect of Opening Size*

The test results for the load-deflection curves for specimens C1, S1, S3, S4, and S5 in which the effect of the opening size was the main investigation parameter, exhibited reduction in the load capacity of the slabs, as can be seen in Figure 5. The reduction in the load capacities were 21 %, 13 %, 14%, and 10% in S1, S3, S4, and S5, respectively.

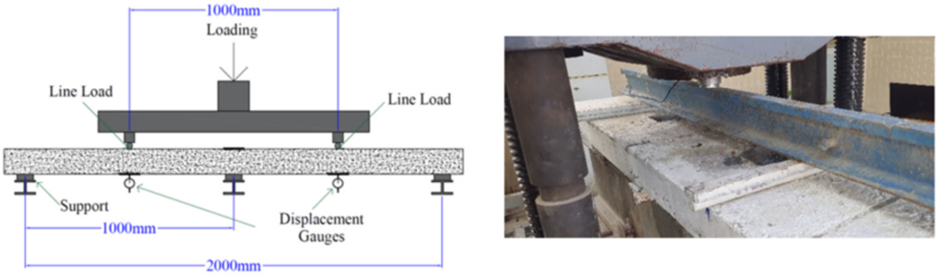

Fig. 3. Testing scheme.

Fig. 4. Failed specimens after test.

TABLE III. TEST RESULTS

Slab No.	First crack load (kN)	Max displace ment (mm)	Yield load (kN)	Ultimate Load (kN)	Ultimate load reduction	Ductility (ultimate/ yield)
C1	130	22	165	230	-	1.39
S1	90	12	135	181	21.3	1.34
S2	100	13	150	186	19.13	1.24
S3	100	18	160	201	12.61	1.26
S4	95	18	152	198	13.91	1.30
S5	100	21	152	207	10.00	1.36
S6	100	20	152	226	1.74	1.49
S7	105	20	150	225	2.17	1.50
S8	95	19	155	225	2.17	1.45
S9	100	19	152	220	4.35	1.45
C2	185	20	300	320	-	1.07
S10	130	16.5	238	260	18.75	1.09
S11	120	18	249	280	12.50	1.12
S12	120	19	275	300	6.25	1.09

The S1's opening size of 160 mm × 160 mm reduced the ultimate load by about 21% in comparison with the control slab C1, while being at the same position but with a smaller size of 100 mm × 100 mm, the S4 opening decreased the ultimate load by about 14%. Therefore, when the opening size decreased from 160 mm × 160 mm to 100 mm × 100 mm, the ultimate load increased by 7%. The same comparison could be made between S3 and S5. S3 had an opening size of 160 mm × 160 mm and S5 of 100 mm × 100 mm. The S3 opening reduced the ultimate load by about 13%, while the S5 opening reduced the ultimate load by about 10% in comparison with the control slab. When the opening size decreased from 160 mm × 160 mm to 100 mm × 100 mm, the ultimate load increased by 3%.

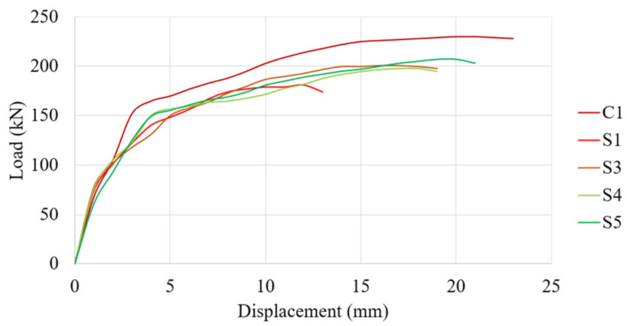

Fig. 5. Load-deflection curves according to opening size.

C. *Effect of the Opening Location*

According to the results of the initial theoretical analysis of the slab, the maximum stresses occurred in the middle support. Due to this fact, the comparison was based on the distance or proximity of the opening from the middle support. The results show a large effect on the distance of the opening from the middle support. S1, S2, and S3 had the same opening sizes with different locations, where S1 was 50 mm from the middle support, S2 was 300 mm, and S3 was 500 mm. S1, S2, and S3 demonstrated a reduction in the ultimate load of 21%, 19%, and 13%, respectively in comparison with C1. Figure 6 shows the effect of the opening location on the load-displacement curves.

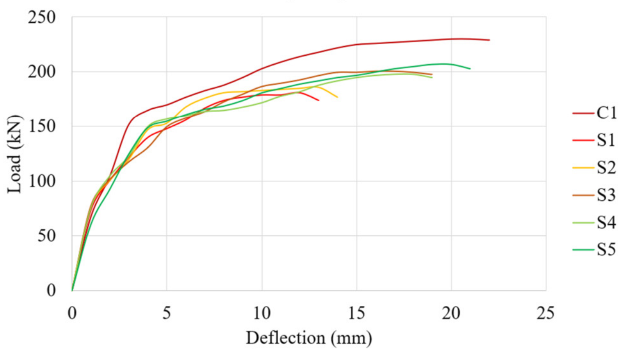

Fig. 6. Load-deflection curves according to opening location.

It is worth mentioning that S1 and S2, unlike the other specimens, failed in shear strength. One of the factors that caused that kind of failure was the location of the opening. In contrast, in the location test, S3 failed in flexural rather than in shear strength. Also, when comparing S4 and S5 with C1, with all of them having the same opening size, 100 mm × 100 mm, but different locations, one close to the middle support and the others far from the middle support, the reduction in the ultimate load of S4 was 14% and of S5 was 10% in comparison with C1. So, the location of the opening affected the ultimate load even when the opening size was reduced.

D. Effect of the Opening Dimensions (Shape).

S3 had the same opening with S8 and the same thickness, but the shape of the opening decreased from the direction parallel to the width of the slab from 160 mm to 100 mm and increased from 160-220 mm in the other direction to 220-100 mm. The shape of the opening reduced the ultimate load by 12%, with the ultimate load of S3 being 201 kN and the ultimate load of S8 225 kN, as presented in Figure 7.

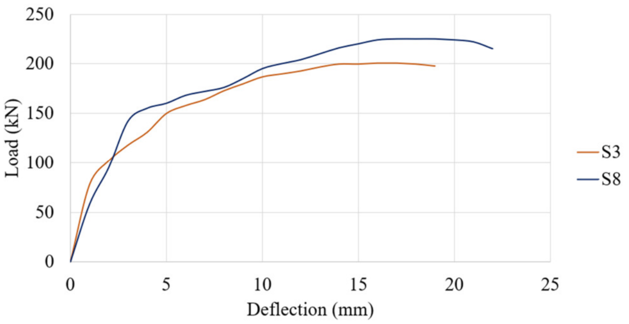

Fig. 7. Load-deflection curves according to opening shape.

E. Effect of the Slab Thickness

The thickness of C1, S1, and S8 was 120 mm, while that of C2, S10, and S11 was 150 mm. The ultimate load of C2 increased by 39% when the thickness increased from 120 mm to 150 mm as in C1, and the ultimate load of S1 increased by 44%, with the same opening pattern in S10. Finally, the ultimate load of S11 increased by 25% compared to S8, which had the same opening pattern. As a result, the opening effect could be reduced by increasing the slab thickness, as portrayed in Figure 8.

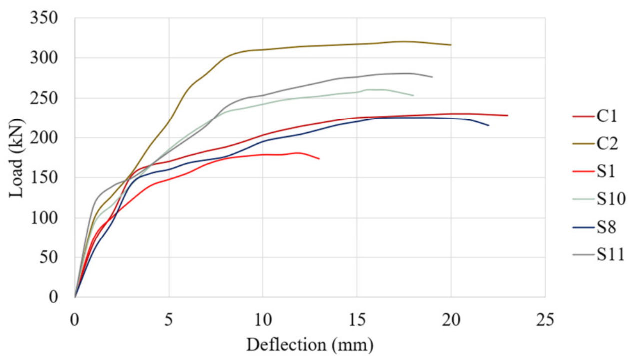

Fig. 8. Load-deflection curves according to opening thickness.

F. Effect of Opening in One Span

S9 and S12 were cast with one opening in the one span whereas the other span did not have any openings. The deflection of each span was approximately the same when comparing the two spans with each other in the same slab. Also, when comparing the deflection and ultimate load of the slab that had an opening in each span with the slab that had one opening in one of its two spans, as in S8 with S9 and S11 with S12, no significant difference was noted, probably because the reinforcement was continuous along the opening sides and the flexural strength was not affected by the opening especially when the opening width was only 100 mm, as illustrated in Figure 9.

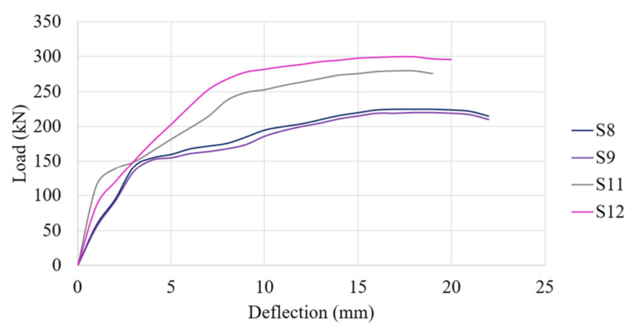

Fig. 9. Load-deflection curves with opening in one of two spans.

G. Effect of Additional Diagonal Reinforcement

According to [25, 26], additional reinforcements should be provided at the corners of the openings in the RC members to enhance the load distribution, prevent cracking, and maintain the general behavior of concrete members. Additional reinforcement was added diagonally at the corners of the S6 and S7 openings which were compared with S1 and S2,. Figure 10 depicts the load deflection results of the four specimens.

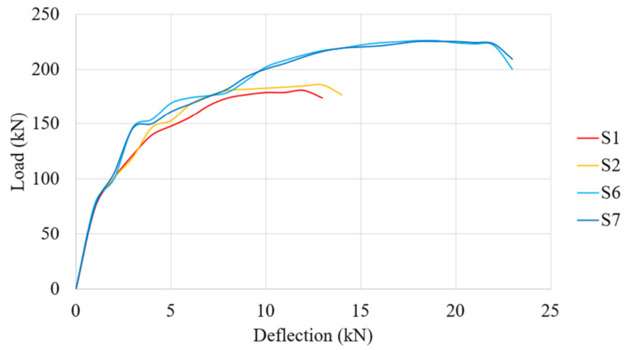

Fig. 10. Load-Deflection curve of additional reinforcement.

The additional reinforcement restored the capacity of the slabs with openings to approximately 98% in comparison with the control slab. The ultimate load of C1 was 230 kN, while S6 and S7 had ultimate loads of 226 kN and 225 kN, respectively.

H. *First Crack Behavior*

Table IV shows the crack load (P_{cr}) for each specimen, the ultimate load (P_u), the percentage of crack load to the ultimate load, and the percentage of the decrease in crack load depending on the crack load of the control slab. The percentage of the crack load to the ultimate load is calculated by:

$$\frac{P_{cr}}{P_u} \times 100\% \qquad (1)$$

The percentage of the decrease in crack load is calculated by:

$$\frac{P_{cr\_control} - P_{cr}}{P_{cr\_control}} \times 100\% \qquad (2)$$

where $P_{cr\_control}$ is the crack load of the control slab.

It is observed that the presence of openings influenced the appearance of the first crack load in the slabs, where the reduction of concrete in the cross-section led to the early appearance of the crack.

I. *Effect of Openings on Ductility*

Ductility is defined as the ratio of post-yield deformation to yield deformation, which usually comes from the steel yield. To calculate the slab ductility, the ultimate load of each slab was divided by the yield load, as shown in Table IV.

The slab ductility was calculated by dividing the ultimate load by the yield load for each specimen. The maximum obtained ductility was that of S7 and the minimum was that of C2, with values of 1.5 and 1.07, respectively. In the case of S7, the additional reinforcement added around the openings, significantly participated to the increase in slab ductility. At the same time, the ductility of S6 was too close to that of S7, which was 1.49, but the openings of S6 were closer to the mid-support. Comparing C1 with S1, S2, S3, S4, and S5, a lack of ductility was noted. The ductility values were 1.39, 1.34, 1.24, 1.26, 1.30, and 1.36, respectively. Given that the openings reduced the slab ductility and that the S5 openings were small and far from the mid support, its value was close to that of C1. On the other hand, C2, S10, S11, and S12 recorded lower ductility values. This occurred because the concrete slab thickness was higher, 150 mm instead of 120 mm, resulting in a lower steel percentage in the slab section, which led to a generally lower ductility.

TABLE IV. FIRST CRACK LOAD

Specimen	Crack load Pcr (kN)	Ultimate load Pu (kN)	(1)	(2)
C1	130	230	57	Control
S1	90	181	50	31
S2	100	186	54	23
S3	100	201	52	23
S4	95	198	56	27
S5	100	207	58	23
S6	100	226	55	23
S7	105	225	53	20
S8	95	225	40	27
S9	100	220	45	23
C2	185	320	58	Control
S10	130	260	50	30
S11	120	280	42	35
S12	120	300	40	35

IV. CONCLUSION

This paper examines the behavior of two-span continuous one-way slabs with openings, focusing on their impact on the ultimate load, yield load, deflection, and ductility. Fourteen slab samples were tested, divided into two groups based on thickness. Each group included one control slab without openings. The locations of the openings were chosen according to the places of high stresses in the structure, which were in the middle support of the slabs. A concentrated linear load was applied on these slabs incrementally and symmetrically on the center of each span. After having tested all specimens and analyzed the results of each slab, the following conclusions were drawn:

- When the opening size changed from 100 mm × 100 mm to 160 mm × 160 mm, the ultimate strength decreased by an average of 17% to 13%.
- The ultimate load reductions of the slabs with openings of 50 mm, 300 mm, and 500 mm from the mid-support, were 21.3%, 19%, and 12.61%, respectively, which leads to the conclusion that the opening location should be as far as possible from the high-stress zones. The slabs that had openings of 50 mm and 300 mm from the mid support failed in shear strength, owing to the high stresses on this zone. In addition, the yield load and ultimate load of S1 were 135 MPa and 181 MPa, respectively, while it recorded the lowest values.
- The effect of the opening shape was noted by comparing the test results of the slabs that had the same thickness and opening location but differed in opening shapes. The slab

with an opening of 160 mm × 160 mm recorded ultimate load of 201 kN, while the slab with an opening of 100 mm in the direction parallel to the width of the slab and 220 mm in the other direction recorded 225 kN ultimate load. That difference emerged from the width variation of the opening.

- When the slab thickness changed from 120 mm to 150 mm, the yield load increased by an average of 77%, and the ultimate load increased by an average of 33%. Conversely, the ductility decreased by an average of 25% due to the lower percentage of steel in the slab section, which leads to a generally lower ductility.
- Finally, the additional reinforcements, added around the openings, enhanced the ultimate load and ductility by an average of 19% and 5%, respectively.

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