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Comparative study on bearing capacity of RC slabs with opening before and after casting

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Abstract
To clarify the load-bearing performance of perforated plates, two-way reinforced concrete slab specimens with the same steel bar arrangement, concrete strength and floor thickness were prepared, one RC slab with opening after casting (named SOAC) and the other was the RC slab with an opening before casting (named SOBC), the pre-production of SOAC specimen without drilling opening was named S0. The concentrated load test of the concrete slab was carried out and crack development, deflection, reinforcement and concrete strains were obtained for each specimen. The results show that drilling will cause greater damage to components with different openings, and the damage range is mainly concentrated around the opening.
Keywords: *Post-opening; Two-way slab; Bearing capacity; Damage*

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I. INTRODUCTION

With the rising of the level and quality of human life, it is becoming much more common to change the using function of existing structures, which often involves introducing openings in existing slabs, such as situating drain pipes, sanitation, ground plugs and buried cable boxes or even warm air supply ducts [1-6]. In addition, because the construction needs to be adapted to new functions, their structural condition often needs to be carefully reassessed [7]. The core-drilling method is a common and reliable method to assess the load-bearing capacity and structural strength of existing structures [8-12]. However, the situation of making openings in existing structures affects the overall slab's behavior and poses a potential risk to the safety of the structure [13-18]. To clarify the degree of damage caused by openings to the members, this study has been carried out on RC slabs with post-openings.

Some overviews of the effects of different opening sizes, numbers, etc. on the load-bearing capacity of open concrete slabs are summarized as follows;(1) the punching shear resistance is decreased with an increase in opening size and with the decrease in opening distance from the column [19], (2) Compared with the corner opening and side opening of the slab specimens, the middle opening of the specimen leads to the increase in the cracking capacity, maximum displacement and maximum strain in the rebar [20], (3) The larger the opening size, the lower the load carrying capacity and stiffness of the slab [21, 22], (4)the reduction in punching shear behavior of Reinforced Concrete (RC) flat slabs can be reduced by increasing the distance between the post and the opening and/or by using circular openings [23]. For two-way RC slabs with multiple openings, the most unfavorable opening locations were the adjacent or parallel openings, and the openings arranged diagonally performed optimal punching behavior than in other cases [24].

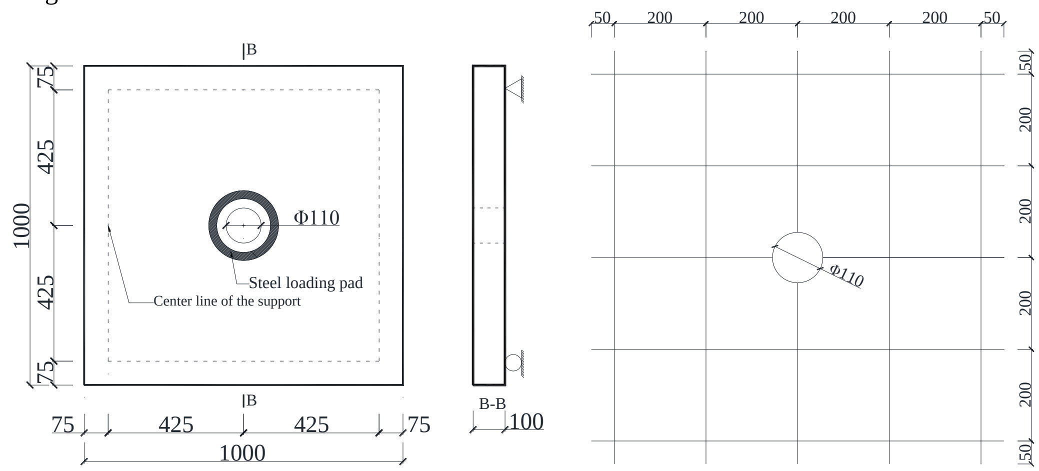
In terms of the ways of introducing openings on RC slabs, Many studies generally focus on how pre-openings affect the mechanical behavior of Reinforced Concrete (RC) slabs. However, most of the research on reinforced concrete slabs with openings only stops at precast openings, which are pre-planned in the design phase. Therefore, to more in line with the actual working conditions and provides a reliable reference basis for the actual working conditions. This research mainly investigates the degree of influence and the range of influence of post-opening on RC slabs and compares the effect on the bearing capacity of RC slabs with opening after casting and before casting.

II. Experimental Program

2.1 Specimens design

A total of two two-way RC slabs (each 1000mm ×1000mm × 100mm) with the same reinforcement arrangement and four-side support conditions were tested. The diameter of the opening is 110mm. The calculated span is 850mm and the support on four edges of the specimens is 150mm. The thickness of the concrete cover is 15mm. One slab (named Slab S0) was a reference slab without openings, while the other slab (referred to as Slab SOBC) was tested with a central opening before casting. The steel bar was configured as

Φ8@200mm with double-layer bidirectional. For the SOBC specimen, the central opening in slabs interrupted four steel bars in each direction in two layers. The geometry and reinforcement details of the specimens are shown in Figure 1.



(a) Slab (b) steel bars

Figure 1: Geometry and reinforcement of specimens

2.2. Preparing the specimens

(1) Concrete mix ratio design

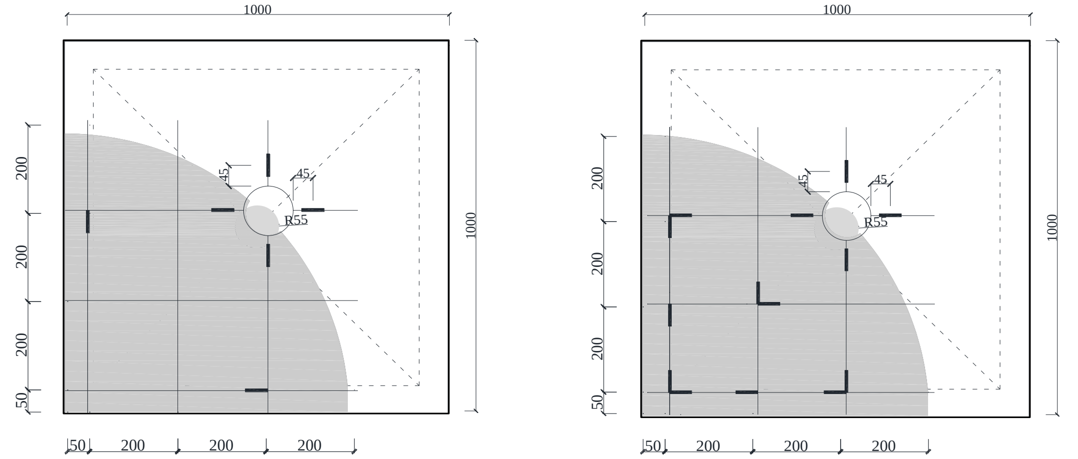
The design strength grade of concrete used in each specimen was C30, and the concrete mix ratio was calculated according to the "Specification for the Design of Ordinary Concrete Mixing Ratio" (JGJ55-2011) [25]. As shown in Table 1. The cement was ordinary silicate cement P-O42.5, and the sand was medium sand with less than 1% of mud. The stone was pebbles with a grain size of 5 to 30mm and pebbles with mud content less than 1%.

Table 1: Concrete mixing ratio.

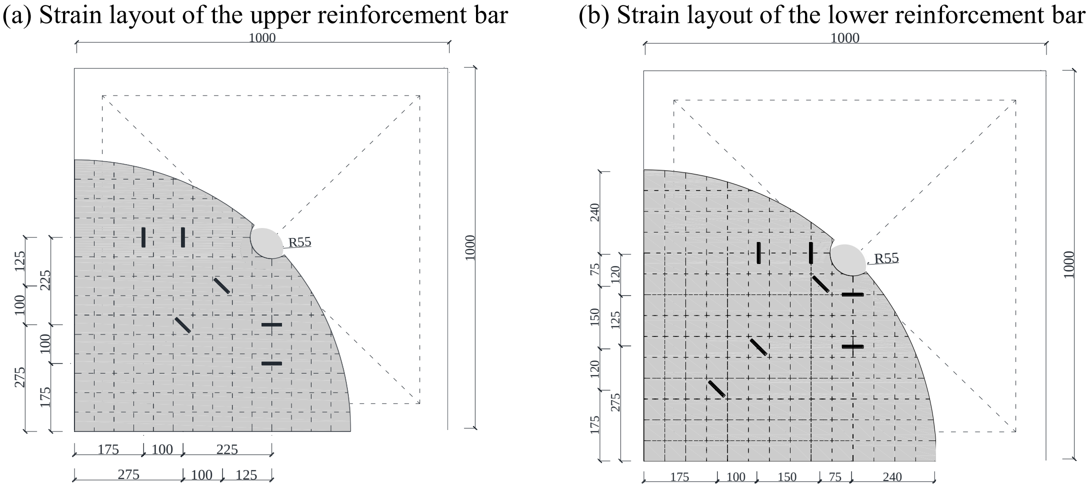
Concrete strength class	Cement (kg/m^3)	Sand (kg/m^3)	Stone (kg/m^3)	Water (kg/m^3)	Water: Cement: Sand: Stone
C30	1.67	3	4.35	1	1：1.67：3：4.35

(2) Layout of strain gauges

Before casting the specimen, a series of reinforcement strain gauges were arranged at the key positions of the reinforcement and concrete in the 1/4 part of the specimen, and the strain gauges on the two specimens corresponded to the same position. The arrangement of strain measurement points of reinforcement and concrete of both specimens SOAC and SOBC are shown in Figure 2.



(a) Strain layout of the upper reinforcement bar (b) Strain layout of the lower reinforcement bar

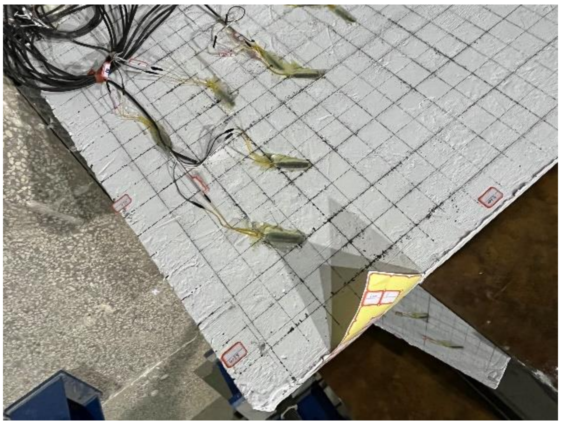


(c) The layout of concrete strain at the top (d) The layout of concrete strain at the bottom

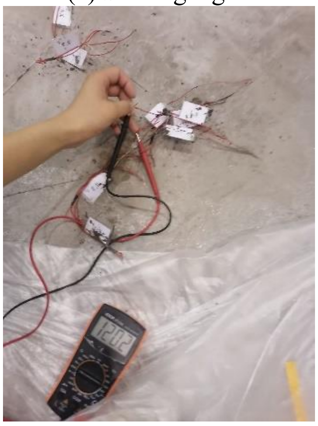
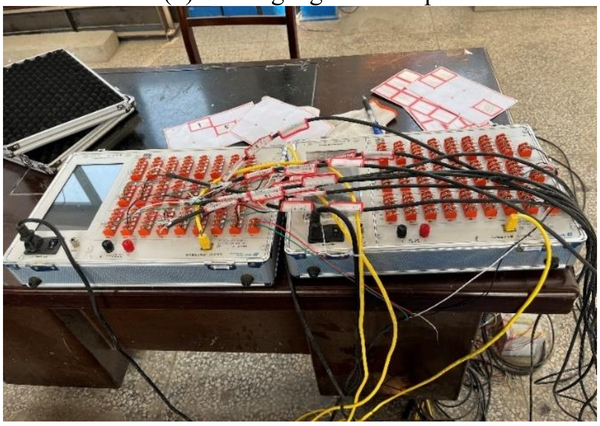
Figure 2: Layout of strain measurement points for RC slab

(3) Strain data collection

The main process of strain data collecting is shown in Figure 3. The digital multimeter is used to test the resistance value of the pasted strain gauges. Then confirming the strain gauges at each measurement point are normal and effective. And led the strain leads out of the cage along the rebar and connected them to the various channels of the DH3818Y static strain tester. Finally, collect and analyze the real-time strain results via the computer software.

(a) Strain gauge attachment (b) Strain gauge surface protection

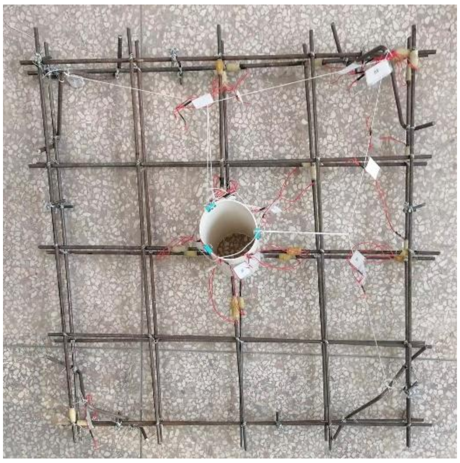
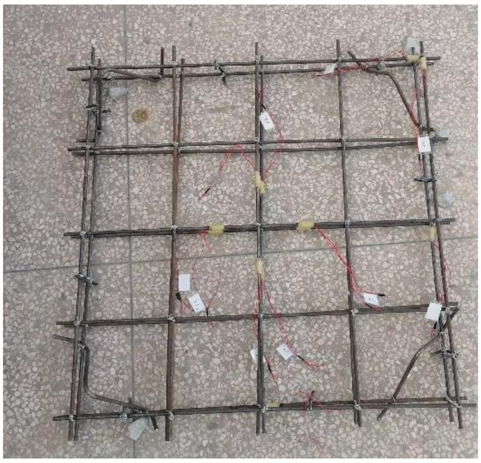



(c) Check the effectiveness of strain gauges (d) DH3818Y static strain instrument

Figure 3: Strain data collection

(4) Binding of reinforcement cage

The reinforcement cage is shown in Figure 4. HPB300 steel bars with a diameter of 8mm are used for binding the steel cage. According to the design size of the floor slab specimen, the steel cage size is 900mm × 900mm. the steel bars in the middle of the steel cage of the SOBC specimen are broken. The formwork for the pre-prepared opening was fixed with the aid of reinforcing bars.

(a) Reinforcement cage for SOBC specimens (b) Reinforcement cage for SOAC specimens

Figure 4: Binding steel reinforcement cage for specimen

(3) Preparation of SOBC specimen

The production process of pre-opened plate specimens is shown in Figure 5. First, install and fix the tied steel cage at the designed position of the formwork, place a 15mm small pad under the bottom steel bar of the slab, and tie the short steel bars between the bottom steel bar and the top steel bar of the slab to ensure that the steel cage is fixed at the designed position. Then thoroughly stir the cement, sand, pebbles, and water together according to the designed mix ratio; pour the mixed concrete from one end of the formwork to the other end into the supported wooden form, and use a vibrator to fully vibrate and compact. After the pouring is completed, use a spatula to smooth the surface, and then cover the upper surface with a plastic film to keep condensation water in the plastic film. After the next day, the specimens were removed from the mold and then covered with geotextile. After that, it was regularly watered and cured for 28 days in the natural environment of the laboratory.

(a) Mixing of specimen concrete (b) Fixing of formwork

(c) Pouring of specimen concrete (d) Vibration of the concrete

(e) Curing of the specimen (f) Finished specimen

Figure 5: Test piece production process for the SOBC specimen

(4) Pre-production of SOAC specimen

The production process of pre-opened plate specimens is shown in Figure 6. The steps for prefabricating the SOAC specimens are made from the same batch of concrete mixture on the same day as the pre-perforated plate specimens. The formwork support, steel cage insertion, concrete pouring and curing processes are the same as those for the pre-perforated plate specimens, but the SOAC The steel cages of the prefabricated specimens were not interrupted during production, nor were any openings made in advance.

Figure 6: Test specimen production process for the SOAC specimen.

(5) Further production of SOAC specimen

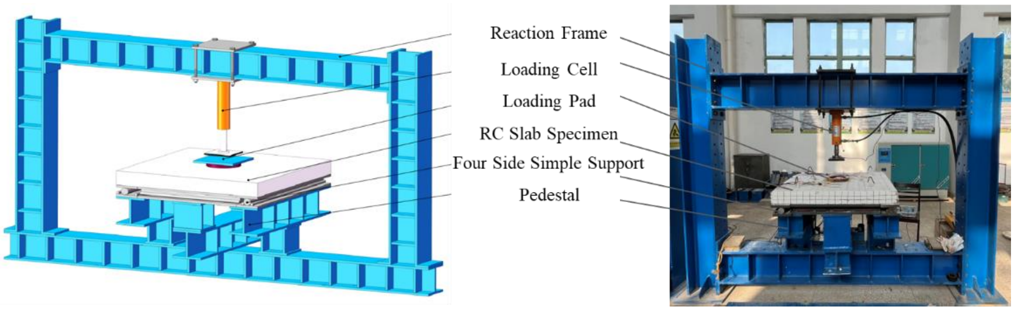
After the SOAC specimen's precast component, S0 completed the concentrated load test in the elastic stage, completed the concentrated load test in the elastic stage, a manual electric drill with a core barrel diameter of 110mm was used to drill openings in the precast component of the SOAC specimen, S0. The drilling position is the same as the SOBC specimen. The drilling opening process is shown in Figure 7.

Figure 7: The drilling opening process of the SOAC specimen

2.3. Loading apparatus and load method

(1) Loading apparatus

Figure 8 illustrates the test setup details. The experimental study was carried out on the slab in the zone enclosed by four steel beams with an 850mm clear span. The specimen rested on supports consisting of two 150mm wide lower and upper steel pads, along with four 80mm diameter round steel rods. The lower pads are welded to the steel plate and concrete, preventing any relative displacement. Two adjacent sides of the round steel rods are welded to the lower pads, and the other two are not, creating a bi-directional plate with simple support on all four sides. A 200kN maximum capacity actuator was used to apply the load. The specimens featured a steel ring simulating a rigid pad, with an outer diameter of 219mm, an inner diameter of 169mm, and a height of 25mm. Loading was achieved using a 300mm × 300mm square steel plate, with the actuator-generated force transmitted to this plate. The loading magnitude was measured by the load cell inside the actuator.



(a) test setup (b) schematic diagram

Figure 8: Support and loading jack.

(2) Loading method

Figure 9 illustrates the details of the test setup. This test employs a uniform gradient loading method. After stabilizing the deformation from the previous load, the next load is applied. The specific load application process is as follows:

i. Before starting the test, a preload of 5kN is applied to ensure the stability of the specimen setup and the instruments' proper operation. Then, unload to zero and record the initial instrument readings.
ii. Load is applied slowly and steadily, increasing by 2kN to 5kN until cracks appear. Before the appearance of any cracks, each load level is increased by 5kN. After applying each load level, the specimen is allowed to stabilize for 10 minutes.
iii. Upon the appearance of cracks, increase each load level by 2kN and maintain stability for 10 minutes.
iv. When the specimen's deflection increment under a certain level of load exceeds the last load level, indicating significant plastic deformation, the load is controlled at a rate of 0.5mm/min.

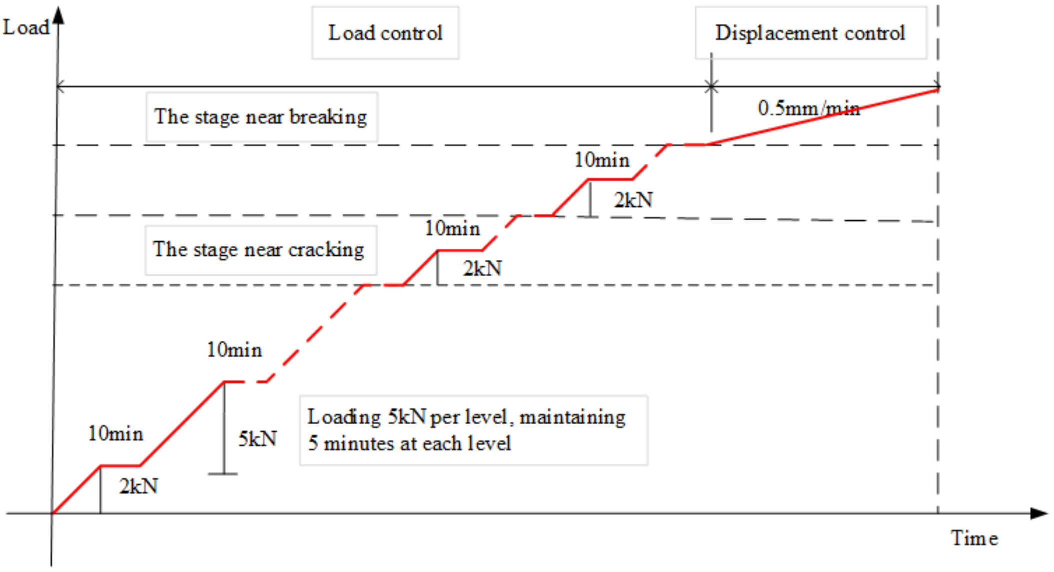


Figure 9: Loading method curve.

III. Results and discussion

3.1 Crack pattern and failure mode

3.1.1 Crack distribution pattern of the SOBC specimen

The distribution of cracks at the bottom of the SOBC specimen is shown in Figure 10.

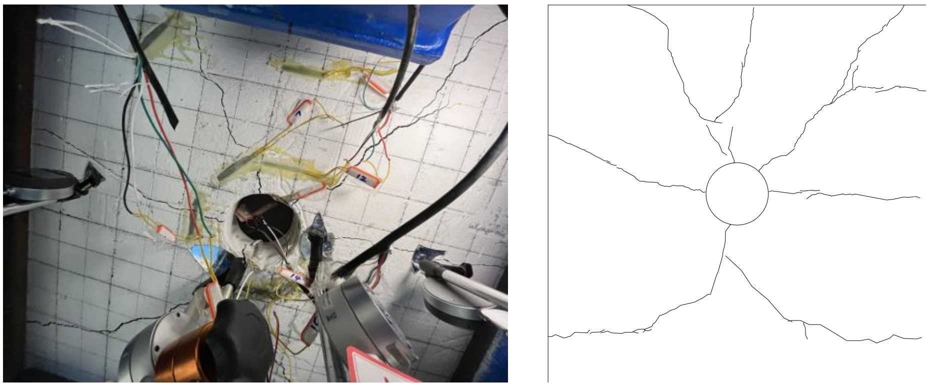
When the load was loaded from zero to 28kN, no cracks appeared in the specimen, the deflection at each measurement point increased linearly, and the reinforcement strain and concrete strain at the bottom of the plate increased linearly with the load, and the plate was in the elastic stress state at this time.

When loaded to 28kN, 2 small cracks appeared along both sides of the opening in the direction of the parallel transverse plate edge, and the first inflection point of the load-deflection curve appeared at this time. With the increase in load, the cracks soon ran through the transverse direction of the slab, and the width of the cracks increased slowly.

When loaded to 48kN, 1 longitudinal crack appeared on the inner side of the opening; when loaded to 52kN, 1 longitudinal crack appeared on the other side of the opening, and diagonal Y-shaped bifurcation cracks appeared along the diagonal direction from the edge of the opening circumference, and branching cracks extending diagonally appeared on the transverse cracks.

When loaded to 56kN, the existing transverse cracks continued to extend from the bottom of the slab along the openings to 3/5 of the slab height, the load dropped abruptly, the deflection increased suddenly, the maximum mid-span deflection reached 13.479mm, other cracks developed rapidly, and the whole damage process was rapid and without obvious premonition.

Thereafter, the loading was changed to displacement control loading, and the cracks at the bottom of the slab became wider and deeper, the crack pattern was radially centered on the openings, and there was no concrete spalling phenomenon.



(a) Crack distribution at the bottom (b)Sketches of the final crack pattern

Figure 10: Crack pattern of the SOBC specimen

3.1.2 Crack distribution pattern of the SOAC specimen

The distribution of cracks at the bottom of the SOAC is shown in Figure 11.

When the load was loaded from zero to 26kN, no cracks appeared in the specimen, the deflection at each measurement point increased linearly, and the reinforcement strain at the bottom of the plate and the concrete strain increased linearly with the load, and the RC slab was in the elastic stress state at this time.

When loaded to 26kN, the first small crack appeared at the bottom of the plate parallel to the direction of the edge of the plate, and the two ends of the crack extended to the edge of the plate bottom support and the opening circumference, and then the first inflection point appeared in the load-deflection curve.

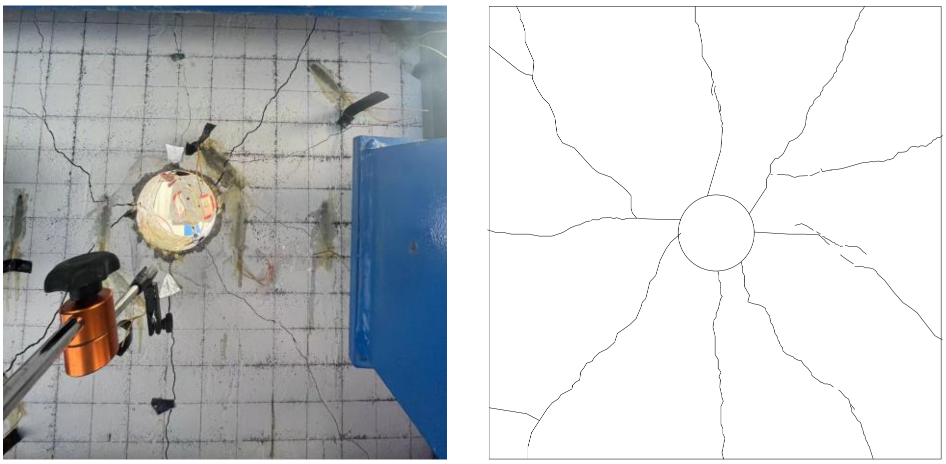
When loaded to 41kN, one new crack was added in the diagonal direction of the bottom of the slab and in the direction parallel to the other slab edge.

When loaded to 45kN, the cracks became more obvious and the width and depth of the cracks increased slowly, with the maximum width of the main crack reaching 1.52mm.

When loading to 50kN, branch cracks extending towards the diagonal direction appeared on the transverse cracks, and the width of the existing cracks increased further; at the same time, a new crack appeared in the diagonal region, and the deflection increased suddenly.

Thereafter it was changed to displacement-controlled loading. One level of loading was applied with every 0.5mm increase in deflection growth in the span, and the maximum load applied was 52kN.

When the specimen SOAC was damaged, the maximum deflection in the span was up to 14.60mm, the cracks on the bottom surface were in the form of a radial pattern centered on the holes, and the concrete near the opening area at the bottom of the plate showed slight spalling, with the maximum width of the main cracks being 2.06mm.



(a) Crack distribution at the bottom (b) Schematic diagram of the SOAC

Figure 11: Cracks distribution on bottom surface

3.1.3 Crack distribution pattern of the test slab

During the testing process, the damage development trend of the two specimens is generally similar. When the specimens were damaged, several vertical cracks extending radially from the bottom to the surface of the slab appeared around the opening on the tensile side of the bottom of the slab, and there was no significant compression failure on the top of the slab.

From the crack diagrams of the specimens at the time of damage, the cracks appeared earlier in the SOAC specimen than the SOBC specimen. The number of cracks in the SOAC specimen was 9 and the number of cracks in the SOBC specimen was 7 at the stage of failure of the specimen. The crack resistance of the SOAC specimen was more deteriorated than the SOBC specimen.

According to test records, the cracking loads of specimens SOBC and SOAC were 28kN and 26kN, respectively, with SOAC's cracking load being 7.69% lower than SOBC's. The maximum loads of specimens SOBC and SOAC are 56kN and 52kN, respectively, with the SOAC specimen's ultimate load being 7.14% lower than SOBC's. This reduction in bearing capacity can be attributed to the different methods of introducing openings in RC slabs; drilling openings in existing slabs has a more significant impact than introducing openings before casting.

3.2 Load-deflection relationship and ultimate load capacity

The load-deflection curves for the tested slabs are shown in Figure 12, For the S0 specimen, y represents the central displacement. For the specimen SOBC and SOAC, y represents the point measured 109.5mm from the center of the circular opening (under the center of the width of the loading steel ring).

As shown in Figure 12, the SOAC specimen had a generally similar evolution trend of load-deflection curves to that of the SOBC specimen under monotonic concentrated loading conditions. Based on the crack growth and the load-displacement characteristics, the loading process can be divided into three distinct stages: (1) Uncracked stage, (2) Pre-yield cracked stage, and (3) Post-yield cracked stage. At the uncracked stage, the load-displacement curves of both specimens exhibited a nearly linear increase with the applied load slowly. In addition, no visible cracks were found in the specimen. The slope of the load-displacement curve of the SOAC specimen was gentler than the SOBC specimen, which is attributable to the impact of the method of cutting the opening. At the pre-yield cracked stage, i.e., the phase occurs from the cracking load to the yield load. The deflection developed nonlinearly with the increasing load, accompanied by micro-cracks emerging at the bottom of each specimen. At the same time, the slope of the curve started to reduce, indicating a decrease in specimen stiffness. At the post-yield cracked stage, the span from the yield load to failure load, the load reached the peak load and then suddenly dropped, and the deflection suddenly kept going up at a high rate.

For the specimen SOBC and S0, it can be observed that the load-defection curves of the solid slab and the SOBC specimen almost coincide at the uncracked stage. This indicates that the effect of opening before casting is not significant at the elastic stage, in agreement with what was reported in the previous studies on slabs with central openings [1, 18, 26].

For the specimen SOBC and SOAC, it can be observed that the slope of the load-defection curves of the SOAC specimen is smaller than that of the solid at the uncracked stage. The reasons may be as follows. Before drilling the opening, the SOAC specimen was subjected to a vertical concentrated load until the slope of the initial linear curve was deflected.

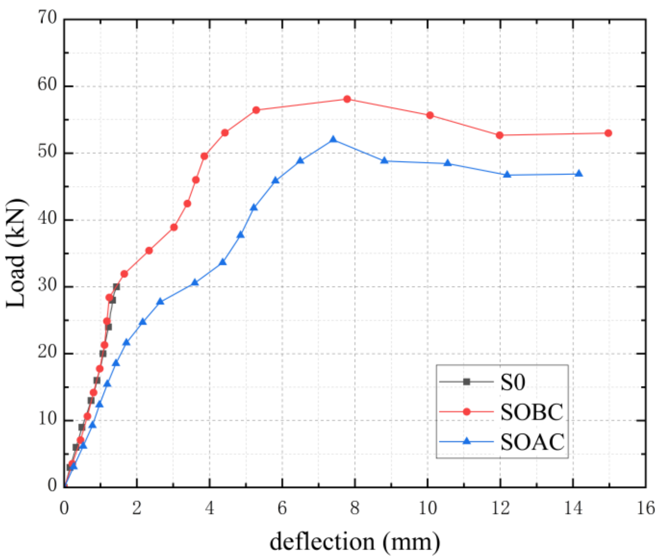


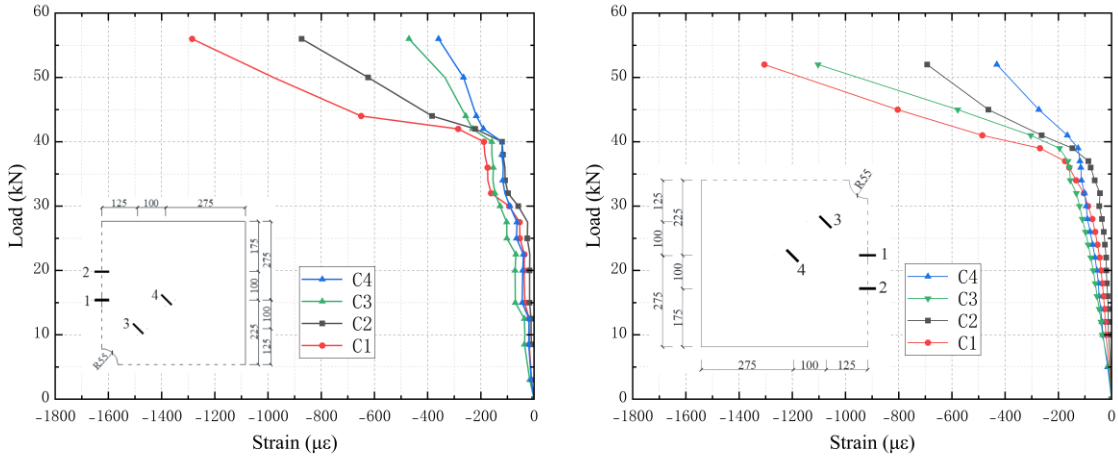
Figure 12: Load-deflection relation for slab specimens

3.3 Strain analysis

3.3.1 concrete strain on the upper surface

The load-strain curves of the concrete at the top of the slab for specimen SOAC and specimen SOBC are shown in Figure 13.

Comparing C3 and C4, it can be noticed that the strain on the upper surface of the plate specimen significantly decreases with increasing distance; Comparing C1 and C3, it can be noticed that the difference in the strain on the upper surface of the test slabs is smaller when the distance from the opening is similar, indicating that during elastic stage, the support constraint exerts minimal influence on the surface strain of the test slabs.



(a) The SOBC specimen (b) The SOAC specimen

Figure 13: Load-strain curve of concrete on the upper surface

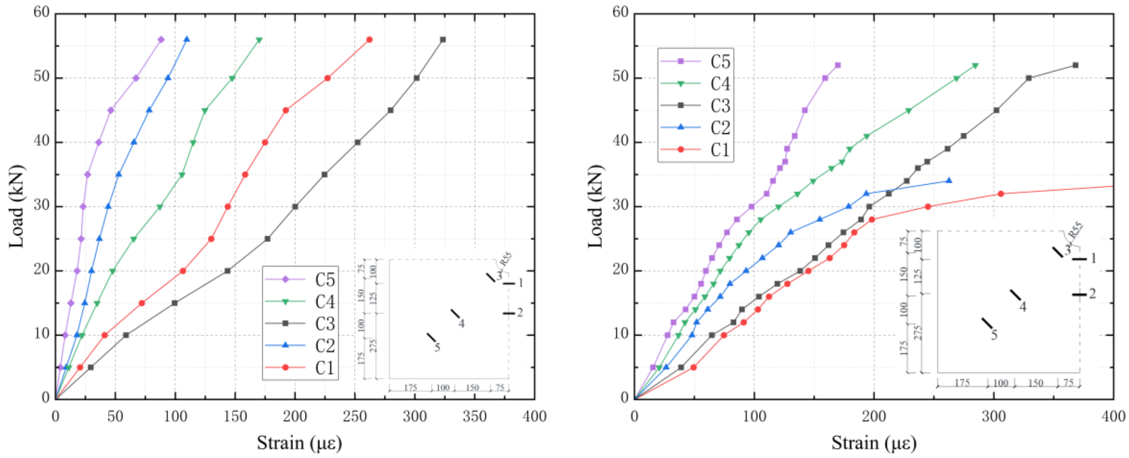
3.3.2 concrete strain on the upper surface

The load-strain curves of the concrete at the bottom of the slab for specimen SOAC and specimen SOBC are shown in Figure 14.

Comparing C1 and C3 against C2 and C4, the strains at C1 and C3 on the specimen SOAC are greater than those at C2 and C4 under the same load. This indicates that introducing openings in the form of drilled openings in existing slabs will cause further damage to the perimeter of the openings.

Comparing C1 and C2 against C3 and C4, the strains at C1 and C3 near the opening are greater than those at C2 and C4 located slightly further away from the opening under the same load, which aligns with the experimental conjecture that concrete strain values are higher near the opening.

For C4 and C5, the load-strain curves are very close, suggesting that the damage from the opening at these two locations is relatively similar.

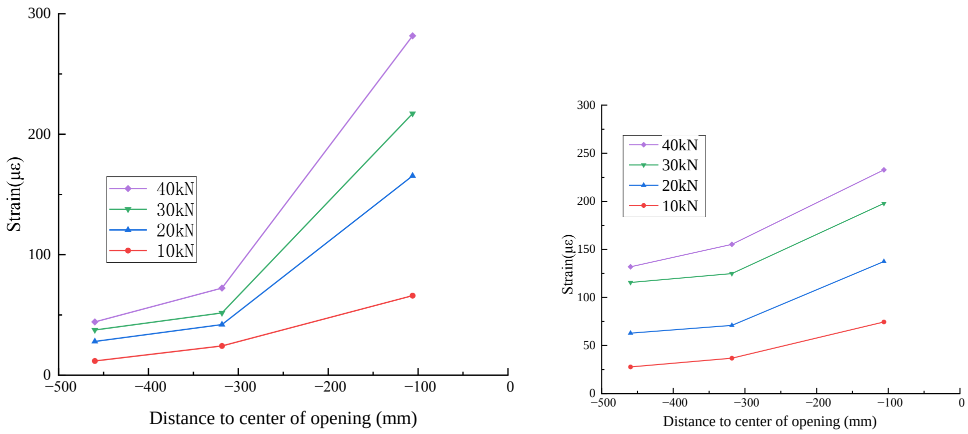


(a) The SOBC specimen (b) The SOAC specimen

Figure 14: Load-strain curve of concrete at the bottom

3.3.3 Strain distribution pattern of specimens

Figure 15 shows the diagonal radial concrete strain distribution curves of specimens SOAC and SOBC under different load levels. The circumferential strain value within 300mm to 500mm from the center of the opening, is smaller. Furthermore, these strain values exhibit minimal variation with increasing load. However, the strain values measured near the opening are significantly higher and the strain rate is much faster compared to those from points further from the opening, which exhibits a marked gradient difference.



(a) The SOBC specimen (b) The SOAC specimen

Figure 15: Strain distribution pattern of specimens

3.3.4 Reinforcement Strain

The load-strain curves of the reinforcement in the mid-span of the specimens are shown in Figure 16. It can be found that the strain values of the tensile reinforcement and the compressive reinforcement were not obvious due to the impact of the opening in the center of the test slabs. This is because the opening on the test slabs interrupted the reinforcement, resulting in small stress on the steel bars and small strain readings.

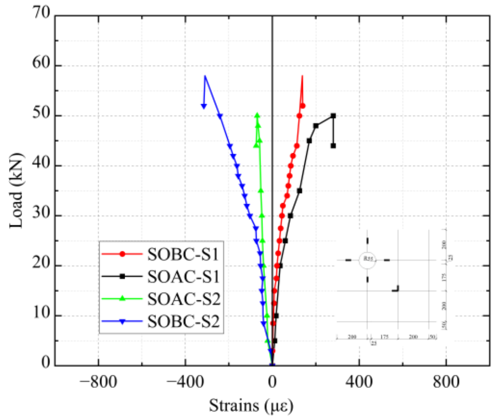


Figure 16: Reinforcement load-strain curves

IV. Conclusion

Based on the results obtained from the experimental work, the following can be concluded:

(1). The damage caused by openings to components is mainly around the opening, and the strain of concrete is generally inversely proportional to the distance from the opening.

(2). The impact of openings on the RC slabs is within a certain range. Mainly reinforcing a certain range around the opening can effectively reduce the stress level and damage degree of concrete.

(3). The opening on the slabs introduced by drilling causes more general damage than the RC slabs with the opening before casting.

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