Punching Shear Strength of Reinforced Concrete Flat Plates with Openings

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ABSTRACT

Test results of six half-scale reinforced concrete flat plates connections with an opening in the vicinity of the column are reported. The test specimens represent a portion of a slab bounded by the lines of contraflexure around the column. The tests were designed to study the effect of openings on the punching shear behavior of the slab-column connections. The test parameters were the location and the size of the openings. One specimen had no opening and the remaining five had various arrangements of openings around the column. All specimens were cast with normal density concrete of approximately 30 MPa compressive strength. The openings in the specimens were square, with the sides parallel to the sides of the column. Three sizes of openings were used: the same size as the column (150 x 150 mm), 67 percent of the column size (100 x 100mm), and 150 percent of the column size (225×225mm). Due to the presence of the openings, the specimens showed a decrease in punching shear capacity ranged between 11.43% and 29.25% with respect to the control solid slab. Also, the stiffness decreased between 0.31% and 83.00%, depending on the size and location of these openings with respect to the column.

KEYWORDS: Flat plates, Openings, Slab-column connection, Punching shear, column.

مقاومه القص الثاقب في البلاطات الخرسانيه المسلحه المسطحه والحاويه على فتحات

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الخلاصه

في هذا البحث تم مناقشته النتائج العمليه لسته بلاطات خرسانيه مسلحه لاكمريه حاويه على فتحات بالقرب من العمود. ان عينات الفحص تمثل جزء من بلاطه محاطه بخطوط انقلاب العزم حول العمود. ان الغرض من هذا البحث هو دراسه تأثير الفتحه على مقاومه القص الثاقب للبلاطات اللا كمريه. وكانت المتغيرات هي موقع وابعاد الفتحه بالنسبه للعمود. احد العينات لاتحتوي على فتحه اما الخمسه المتبقيه فكانت تحتوي على ترتيب مختلف من الفتحات حول العمود. الفتحات كانت مربعه الشكل وبابعاد موازيه لابعاد العمود. تم استخدام ثلاث ابعاد للفتحات وهي: مساويه لابعاد العمود (150×150ملم) و 67% من ابعاد العمود (100×100 ملم) و 150% من ابعاد العمود (225×225ملم). نتيجه لوجود الفتحات في البلاطات تناقصت مقاومه القص الثاقب بين 11,43% الى 29,25% مقارنة مع بلاطه بدون فتحه كذلك قلت الصلاده بمقدار 0,31% الى 83% عتمادا على ابعاد وموقع تلك الفتحات حول العمود.

الكلمات الرئيسيه:البلاطات المسطحه، فتحات، الارتباط بين البلاطه والعمود، القص الثاقب، العمود

1. INTRODUCTION

Reinforced concrete flat plate structure is a widely used in low to medium-rise multistory buildings, it consists of a floor or a roof of a uniform thickness carried directly by prismatic columns. The drop panels, column capitals and spandrel beams are omitted.

Since 1950, flat plate slab has proved economical in tall apartment house construction (Ferguson, 1981), it is preferable in bridge decks and multi-storey structures such as office buildings and car parks for many reasons such as its simplicity and accelerating site operations in addition to its allowance for easy and flexible arrangement of columns, partitions and hence reduction of the overall height of tall buildings (McCormac, 2001).

The critical problem in the design of concrete flat plate is the concentration of shear stresses around the column-slab connection which can cause abrupt punching shear failure at loads far below the slab flexural strength. Punching shear failure of the slab is usually sudden and leads to a progressive collapse of the flat plate structures. The local and brittle nature of the punching shear failure in the form of column punching through the slab along a truncated cone is caused by a diagonal cracking around the column (Hong and Yew-Chang, 2003).

In flat plate floor systems there is often a need to install new services that required openings in the vicinity of columns. The openings are required mainly for sanitary reasons, ventilation, heating, air conditioning and electrical ducts. The existence of the opening takes away part of the volume of concrete responsible for resisting shear force and unbalanced moment, which in turn further reduces the punching shear capacity of the slab-column connection. The connection is therefore more vulnerable to brittle punching shear failure.

Over the past 100 years only a moderate amount of research has been conducted on punching shear strength of flat reinforced concrete slabs with openings in the vicinity of columns, in comparison with other subjects matter in structural engineering. This is reflected in the codes of practice covering the design of such structural systems where the conservative nature of code predictions has been widely recognized (Guan, 2009). Moe (1961) conducted an investigation focused on the failure of reinforced concrete slabs and footings in shear, where a wide range of experiments were conducted on a variety of different slabs with openings adjacent to the columns. Hognestad et al. (1964) carried out further laboratory tests on slab- interior column connections with openings with particular emphasis on lightweight aggregate concrete slabs. Not until the mid 90's that studies on the punching shear behavior of slab-column connections with openings have regained researchers' attention (Guan, 2009). Various laboratory investigations have been conducted including openings in the vicinity of square columns by El-Salakawy et al.(1999), Teng et al.(2004), and Bompa and One (2010). However, these researches seem to be limited. The tests reported in this paper partially fill this void.

2.RESEARCH SIGNIFICANCE

In design and construction of reinforced concrete members, the shear failure should be prevented. Openings near the columns decrease the punching shear capacity of slab. Therefore, understanding the behavior of slabs with openings is important for developing safe design procedures.

3. TEST SPECIMENS

The test specimens were half-scale and represented interior columns connected to a slab bounded by the lines of contraflexure around the column. The dimensions of the specimen were defined by performing the analysis of a typical floor system consisting of three 4.25m bays in one direction and an infinite number of 4.25m bays in the other. The resulting test slabs were 70mm thick and had in-plane dimensions of 1000×1000 mm. the columns' cross sections were 150mm

square and the high of the columns above the slab was 200mm (**Fig.1**).

A total of six specimens (XXX, SF0, CF0, LF0, CC0, and CF1) were tested. The main parameters were the location and the size of the opening. All openings in the specimens were square with the sides, of length *l*, parallel to the sides of the column ,*c*. Three sizes of openings were used: (150×150mm) with *l/c*=1, (100×100mm) with *l/c*= 0.67, and (225×225) with *l/c*=1.5, where *c* is the length of the side of the column (**Fig. 2**).

The specimen designation can be explained as follows. The first letter indicates the size of the opening(C= column size= 150×150mm, S=smaller size=100×100mm, and L=larger size= 225×225mm). The second letter indicates the position of the opening around the column (F=front and C=corner), and the third letter indicates the distance D of the opening from the column face, divided by the thickness of the slab h (D/h=0, and 1). In case of a solid slab (without opening), the designation (XXX) is used. The entire characteristics and details of the tested specimens are listed in **Table 1**.

All specimens were supported on the (900×900mm) perimeter on the bottom of the slab. The top of the specimen represents the slab compression surface under vertical load. This is opposite to the situation in a real slab-column system where compression is on the bottom.

All specimens were reinforced by one bottom layer of (6mm in diameter) steel bars, spaced (75mm) c/c in each direction and arranged to give an average effective depth ($d_{av.}$) of (54mm). All column stubs were reinforced with four (12mm) longitudinal bars and (6mm) as transverse reinforcement (ties). The openings were not bordered with reinforcement as it used and requested by code design specifications. This condition was imposed in order to find out which is the quantum when bordering is passed over and the cut in slab is made on site without accounting the possible loss of strength in the control perimeter.   The reinforcement details of the specimens are shown in **Fig. 1**.

The specimens were constructed using a normal density concrete with a compressive strength of approximately 30 MPa. The concrete was produced in the laboratory using normal portland cement, fine aggregate, and crushed coarse aggregate of 10 mm maximum nominal size. **Table 1** lists the final strengths based on the average values from the tests performed on at least three 150 x 300mm cylinders for each test specimen. The tensile strength of the concrete was determined by performing the split cylinder tests. The properties of the steel used in the reinforcing mats of the slabs are listed in **Table 2**.

4. TEST PROCEDURE

All specimens were tested using the hydraulic testing frame (**Fig. 3**). Flat plate specimens were placed inside the testing frame so that support lines, point load and dial gauges were fixed in their correct locations. The specimens were then loaded centrally through the column stub with monotonically increasing load until failure. The load was applied slowly in increment of (3.5 kN) using a hydraulic jack of (1000 kN) capacity.

At each loading stage, the test measurements included the magnitude of the applied load, deflection of the slab at five locations(**Fig.4**), first crack width, and strain in compressive face of slab were recorded.

At the end of each test, the angle at which the shear cracks propagated away from the column face was measured and the crack pattern and mode of failure for each specimen were carefully examined.

5. TEST RESULTS AND DISCUSSION

5.1. General Behavior and Crack Patterns

Six specimens failed in a brittle sudden punching mode. Under loading, the first cracks (flexural) occurred at a load range of about (21.1% to 28.6%) of the ultimate punching capacity of the specimens. The cracks first started with diagonal cracks running from the corners of the column stub toward the slab edges on the tension side. As

the load was increased, circumferential cracks occurred at a location farther away from the column stub and developed gradually over the entire slab. At load of (54.9% to 63%) of the failure load of the specimens, the flexural cracks reached all the way out to the edges of the slabs. The first cracks generally reached the edges at a distance equal approximately 201 to 324 mm from the corners of the slab.

The formation of inclined shear cracks was visible inside the openings during testing of interior slab-column connections. These cracks developed at approximately (40-80%) of the failure load at an angle of approximately (26-53) degrees. The inclined shear cracks usually started from flexural cracks. Very often these flexural cracks first developed in the corner of the opening.

In Specimens **SF0**, **CF0**, and **LF0** (openings immediately adjacent to the face of the column), the first cracks started in the nearest corners of the opening to the column, and propagated to the edges of the slab. At load of (48%-59%) of the ultimate load, other cracks formed in the farthest corners of the opening, and propagated to the corners of the slab.

In Specimen **CC0** (opening immediately adjacent to the corner of the column), the first cracks initiated in the corner of the opening near the column. Other cracks formed in the opposite corner at approximately 40% of the failure load and migrated to the nearest corners of the slab.

In Specimen **CF1** (opening at distance of 70mm from the column face), the first cracks formed between the corners of the column and the closest corners of the opening, instead of developing from the column corners to the slab edges. At slightly larger load, other cracks started from the farthest corners of the opening and migrated to the corners of the slab. The inclined cracks that caused failure for this specimen did not start at the corner of the opening, but traveled approximately straight through the opening at mid-distance between the corners.

In general, signs of punching failure in specimens were evident in the formation of one major circumferential crack, away from the column face and the sudden and brittle punching of the column stub through the slab. While punching of the column stub through the slab at the compression face occurred at the face of the column.

The cracks pattern at the tension and compression face as well as inside the openings for all specimens after failure are shown in **Fig. 5 to 10**. In all specimens, the shear failure cone ranged on average from 154 to 191mm from the face of the column which corresponds 2.86 to 3.54d, where d is the effective depth of the slab.

5.2. First Cracking and Ultimate Loads Results

In order to compare the test results of specimens with different compressive strength, the measured load of each specimen is normalized to the concrete compressive strength of the control Specimen **XXX** (35.69 MPa). The normalized load is obtained by multiplying the measured load by $(35.69/f_c')^{1/2}$. Where f_c' is concrete compressive strength of the individual specimen in MPa. This method, to compensate for the differences in a concrete strength, was adopted in the most previous researches conducting on punching shear strength of concrete flat plates (El-Salakawy et al. (1999), Harajli and Soudki (2003), Polak et al. (2003), Sharaf et al. (2006), Soudki et al. (2012))

The experimental results for cracking and ultimate loads of all specimens are given in **Table 3**. The test results show that, due to the openings existence, both the cracking and ultimate loads decreased in comparison with the reference Slab **XXX** (solid slab) depending on the sizes and locations of these openings.

The size of the opening has a significant effect on the capacity of the slab. For specimens with openings located directly next to the column, the normalized cracking and ultimate loads of Specimen **LF0** with larger opening (225×225mm) decreased by 47.87% and 29.25% respectively in comparison with the normalized cracking and

ultimate loads of Specimen **XXX**, while for Specimen **SF0** with smaller opening (100×100mm), the decreasing in the normalized cracking and ultimate loads are 14.15% and 12.42%, respectively. This means in other words, the bigger the opening size the larger the reduction in both normalized cracking and ultimate loads, as shown in **Fig. 11**. It can be seen that, the reductions in normalized cracking and ultimate loads are proportional to the ratio of the opening size to the column size. Additionally, with increasing the opening size there is more rapid increase in the reduction in the normalized cracking load, which is always larger than that in the normalized ultimate load especially when the opening size is greater than the column size.

The distance between the column edge and the opening influences the cracking and ultimate loads of the concrete flat plate. For Specimen **CF1** with a 150×150mm opening located at the distance of 70mm from the front edge of the column, both the normalized cracking and ultimate loads decreased by 13.5% with respect to the cracking and ultimate loads of Specimen **XXX**. For Specimen **CF0** with the same size opening located directly next to the column, the normalized cracking and ultimate loads are 23.28% and 19.65% smaller than those of solid Specimen **XXX**, respectively. **Fig. 12** shows that, the further the opening from the column face, the lower the reduction in both the normalized first cracking and ultimate loads.

The arrangement of the openings around the column also affects the cracking and ultimate loads of the slab. For specimen **CC0** where 150mm square opening is immediately adjacent to the corner of the column, there is the smallest influence of the opening on its punching shear capacity. The normalized first cracking load decreased by 13.22% and the normalized ultimate load decreases by 11.43%. This reduction in normalized loads is quite small comparing to specimen **CF0** with the same size opening located next to the front of the column. These results are expected because the opening at the corner of the column has a smaller effect on the area and the

inertia of the critical shear section than that opening at the front edge of the column.

5.3. Load-Defection Response

Figs.13 and 14 compare the normalized load-central deflection response of all six tested specimens. It is clear that, the deflection characteristics are similar for all slabs. In general, the normalized load- central deflection response can be divided into uncracked and cracked stages. The cracked stage can be divided into two substages: a preyield stage and a postyield stage. The preyield cracked stage is from the cracking load to the yield load. The postyield cracked stage extends from the yield to the punching failure load.

The behavior of the specimens with openings is compared to the behavior of specimen **XXX** (without an opening) at two load stages: a service load stage and the failure load stage. The serviceability limit is about 70-75% of the peak load (Tan and Zhao, 2004). In the presented discussion of deflections, the service loads are equal to 71.16 kN (70% of the peak load of control specimen **XXX**). The failure loads are equal to the recorded failure load, as listed in **Table 3**.

The influence of the size of the openings on normalized load- central deflection behavior is demonstrated in **Fig.13**, where the results for **SF0** (with a 100×100mm opening), **CF0**(with a 150×150mm opening), and **LF0**(with a 225×225mm opening) are compared with **XXX**, the control specimen without opening. The experimental results confirm that, the larger the opening the larger the reduction in slab stiffness or in other words, the larger the deflection at the same load level. However, the influence of the opening size on the recorded deflections at service stage is relatively small when the opening size is less than the column size as in specimen **SF0**, where the maximum measured deflection at normalized service load is 3.37% larger than that of control specimen. At failure, this percentage

increases to 32.18%. The effect of the opening becomes more significant when the opening size exceeds the column size as in specimens **LF0**, where the maximum recorded deflection at normalized service and failure loads are 83% and 83.23% respectively larger than those of specimen **XXX**.

Fig.14 illustrates the effect of the opening location on normalized load- central deflection behavior, where the behavior of specimens with 150 mm square openings that constructed at different locations is compared with the behavior of the solid slab **XXX**. It can be seen that, there is a significant increase in the recorded deflection at normalized service load for specimen with front edge opening (**CF0**) about 30.63% over the control slab, while at failure this percentage becomes 57.47%. For two other specimens, the increases in the recorded deflections at normalized service load are relatively small, which are 0.31% and 7.50% for specimens **CC0** and **CF1**, respectively. At failure, these percentages become 23.06% (**CC0**) and 27.07% (**CF1**), as listed in **Table 4.**

5.4. Cracking Behavior of Specimens

In general, slabs with openings have maximum crack width larger than the reference slab (**XXX**) during the same stage of loading. The existence of opening in concrete slab-column connection reduces the rigidity of the connection depending on the size and location of this opening and that reflects the increase in the crack width. This is illustrated in **Figs. 15 and 16**.

Fig. 15 compares the crack behavior of specimens with openings immediately adjacent to the column front face with the crack behavior of specimen **XXX** to study the effect of the opening size. There is significant increase in the crack width with increasing the size of the opening as shown in Fig. **Fig. 15**. At load level of 71.16 kN that represents service load in solid slab **XXX** as mentioned previously, the maximum crack width measured in specimen with smaller opening size (**SF0**) is 66.48% over the solid slab. This percentage

increases to 296.35 % for specimen with larger opening size (**LF0**).

The influence of the opening location on the cracking behavior of specimens is shown in **Fig.16**. In specimen **CF0** with front face opening, the maximum crack width at normalized service load is 159.97% larger than the maximum crack width of specimen **XXX**. The increase in the maximum crack width at normalized service load becomes 108.55% when the opening is immediately adjacent to one of the column corners (**CC0**). In specimen with opening located away from the front column face (**CF1**), the maximum crack width increases about 72.21% over the solid slab at normalized service load.

At failure loads of specimens, the values of maximum crack width for specimens with openings are generally larger than that of solid control slab at the same load level and ranged between 71.82% and 296.99% over the control specimen **XXX**. However, the values of crack width beyond 0.41mm are not important because the slabs are out of the serviceability stage (Nilson et al., 2004).

5.5. Concrete Compressive Strains

Concrete strains were measured using demec points where placed on the compression side of specimens to observe the strain level at punching. The position and direction of the demec points are shown **Fig. 17**. The test results show that, both the tangential and the radial strains at ultimate loads for each specimen were inversely proportional to the distance from the column stub. In addition, with increasing distance from the column stub there was a more rapid decrease in the radial strains, which were always smaller than the tangential strains.

Figs. 18 and 19 show the relations between normalized load and maximum concrete compressive strains for the tested slabs. The maximum strain values for all specimens were recorded at line L_1 (between two demec points) nearest to the column stub in tangential direction perpendicular to that passing through opening.

The figures show that specimens with openings have maximum concrete strains larger than of solid specimen at the same stage of loading depending on the location and size of the opening. In other words, the bigger the opening size the greater the maximum concrete strains and for specimens with same opening size, the closer the opening to the column front face the greater the maximum concrete strains.

6.SUMMARY AND CONCLUSIONS

The main conclusions can be summarized as follows:-

1.   All specimens failed in punching shear mode.

2.   The size of the opening affects the capacity of the flat plate. The ultimate strength of the flat plate with the larger opening decreased by 29.25% with respect to the ultimate strength of solid specimen. For the specimen with a smaller opening, the decrease in capacity was12.42%.

3.   The further the opening from the column, the higher the ultimate strength of the connection. For the specimen with opening at distance h (70mm) from the front face of the column, the shear capacity decreased by 13.47% from control one. For specimen with the opening next to the column, the decrease in capacity was 19.65%.

4.   The opening located at the front of the column decreases the shear capacity of the flat plate more than the same size opening located at the corner of the column. The opening location adjacent to the front column face decreased the shear capacity by 19.65% from control one, while that adjacent to the column corner decreased the capacity by 11.43%.

5.   The presence of openings in flat plates decreases the stiffness depending on the sizes and locations of these openings. For the specimen with the opening of the 1.5 size of the column, significant reduction in stiffness

(83.00%) at service stage was observed, while for slabs with smaller openings, the reduction in stiffness was much smaller (0.31to 30.63%).

6.   Slabs with openings have maximum crack width larger than what observed in the reference slab during the same loading stage. The increase in maximum crack width at service load ranged between 66.48% to 296.35 % with respect to solid specimen.

7.   The existence of openings increases the strains in concrete on the compression face of the slabs. Generally, the bigger the opening size the greater the maximum concrete strains and for specimens with same opening size, the closer the opening to the column front face the greater the maximum concrete strains.

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Table 1: Summary of Test Data

Specimen designation	Opening size, mm	Opening location around column	Distance of opening from column, mm	Age of slab (from casting to testing, days)	Compressive strength at time of slab testing f_c' (MPa)	Splitting tensile strength ft at time of slab testing (MPa)
XXX	N/A	N/A	N/A	90	35.69	3.61
SF0	100×100	Front	0	95	37.10	3.50
CF0	150×150	Front	0	103	34.13	3.44
LF0	225×225	Front	0	108	32.83	3.01
CC0	150×150	Corner	0	109	36.27	3.29
CF1	150×150	Front	70	110	36.50	3.37

Note: N/A not applicable

Table 2: Properties of Steel Reinforcement

Nominal diameter (mm)	Measured diameter (mm)	Yield Stress f_y (MPa)	Ultimate Strength f_u (MPa)
6	5.83	598	657
12	11.87	648	721

Table 3: Cracking and Ultimate Loads of Test Specimens

specimen	Experimental load, kN		Normalized load,kN *		% decrease in first cracking load with respect to Control slab (XXX)	% decrease in ultimate load with respect to Control slab (XXX)
	First cracking load,P_{cr}	Ultimate loads,P_u	First cracking load,P_{ncr}	Ultimate loads,P_{nu}		
XXX	29.04	101.65	29.04	101.65	0	0
SF0	25.41	90.76	24.93	89.02	14.15	12.42
CF0	21.78	79.87	22.28	81.68	23.28	19.65
LF0	14.52	68.98	15.14	71.92	47.87	29.25
CC0	25.41	90.76	25.20	90.76	13.22	11.43
CF1	25.41	88.94	25.13	88.95	13.46	13.47

* Normalized load= experimental load $\times \sqrt{(35.69/f_c')}$.

Table 4: Central Deflections of Tested Specimens at Normalized Service and Ultimate Loads

specimen	Deflection at normalized service load Δ_{ns} (mm),	% Increase in deflection*	ultimate load of individual specimen(kN)	Deflection at normalized ultimate load Δ_{nu} (mm)	Deflection of control specimen (XXX) at ultimate load of individual specimenΔ_{nuc}(mm)	% Increase in deflection at ultimate load**
XXX	6.53	0.00	101.65	15.91	15.91	0.00
SF0	6.75	3.37	89.02	14.46	10.94	32.18
CF0	8.53	30.63	81.68	13.81	8.77	57.47
LF0	11.95	83.00	71.92	12.24	6.68	83.23
CC0	6.55	0.31	90.76	13.98	11.36	23.06
CF1	7.02	7.50	88.95	13.33	10.49	27.07

$$* \frac{\Delta_{ns} - \Delta_{ns(control)}}{\Delta_{ns(control)}} \times 100\%$$

$$** \frac{\Delta_{nu} - \Delta_{nuc}}{\Delta_{nuc}} \times 100\%$$

Unit:mm
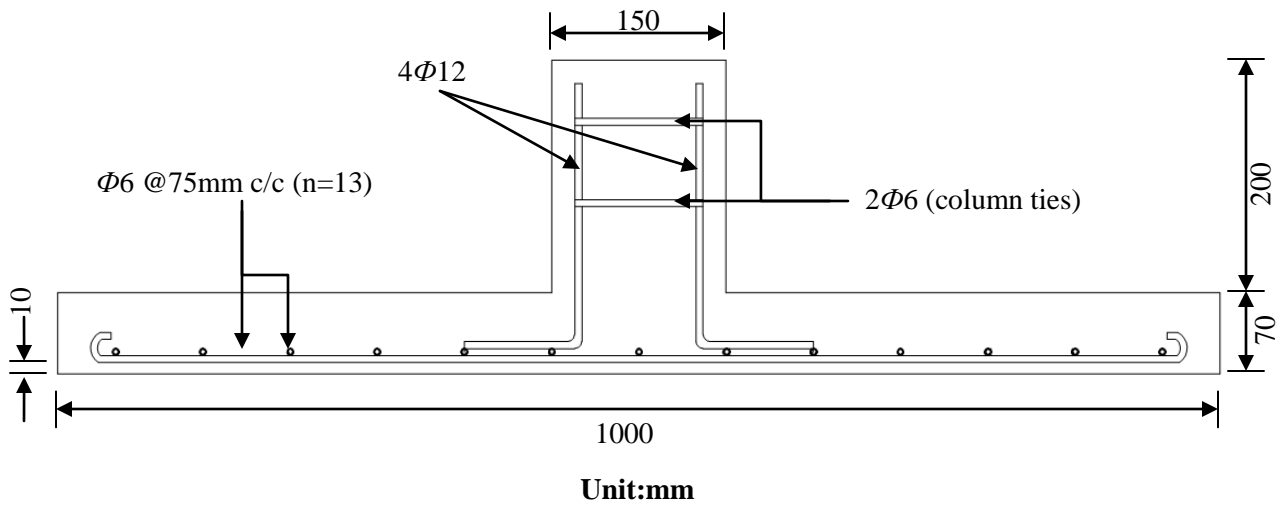
Fig. 1: Details of Half-Scale Model Slab
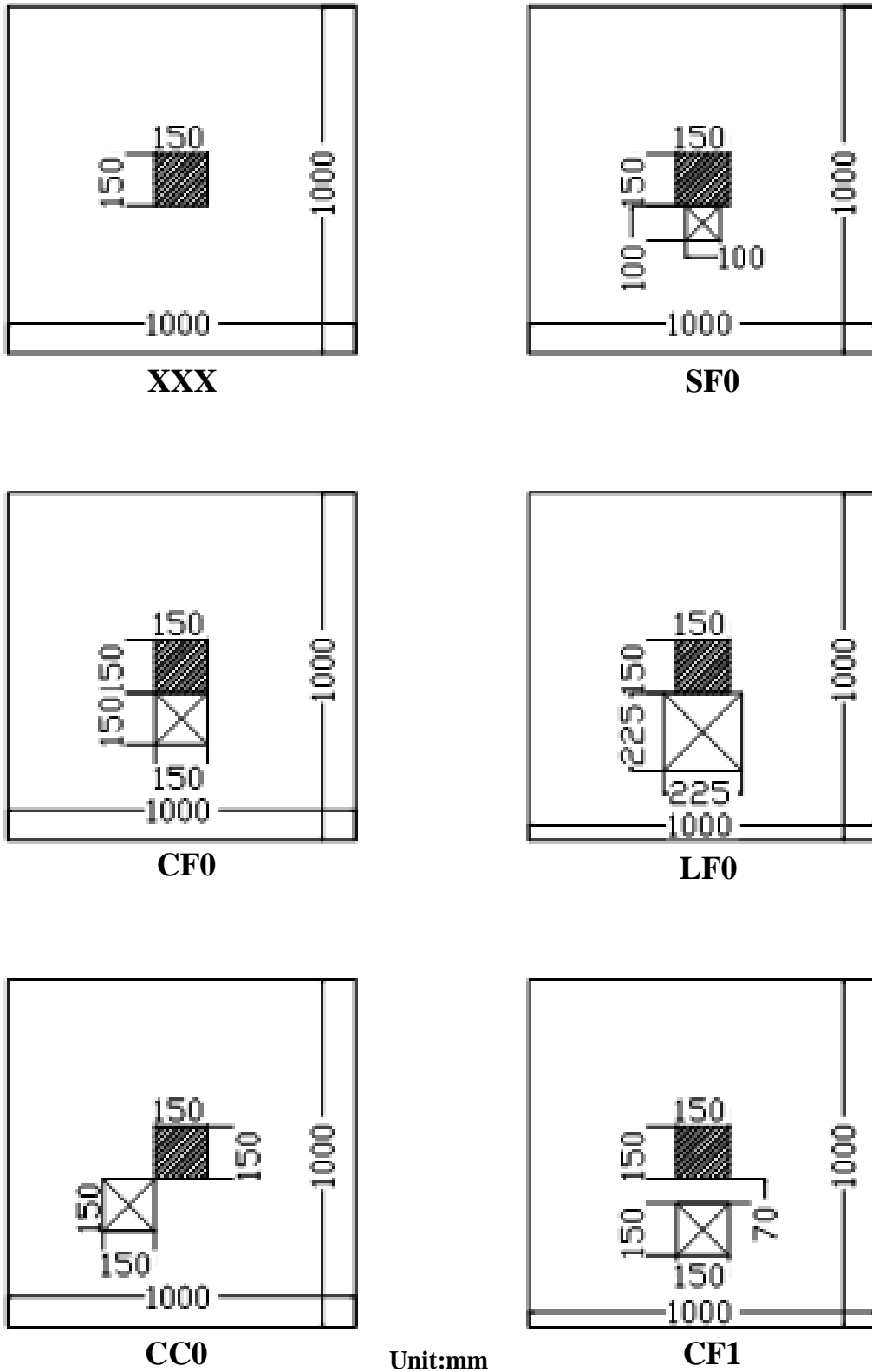
Fig. 2: Plan View of Test Specimens

Unit:mm

11

(b) Supporting Ring Beams

(a) Specimen inside the Testing Frame

Fig.3: Testing Frame
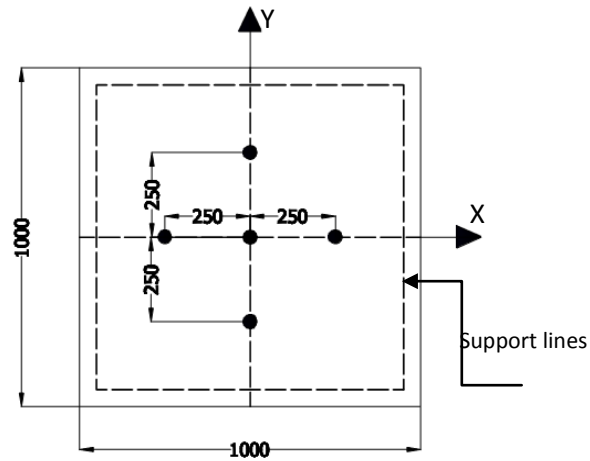
Fig. 4: Arrangement of the Dial Gages
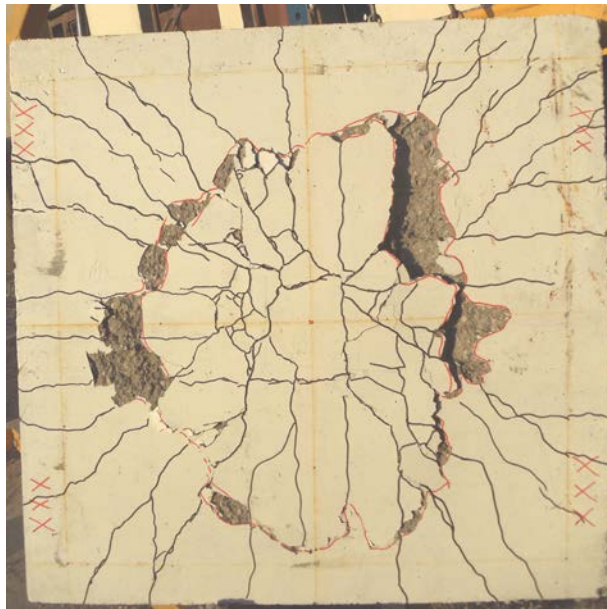
(a) Tension face   (b) Compression face

Fig.5: Cracks Pattern for Specimen XXX (Solid Slab) after Failure.
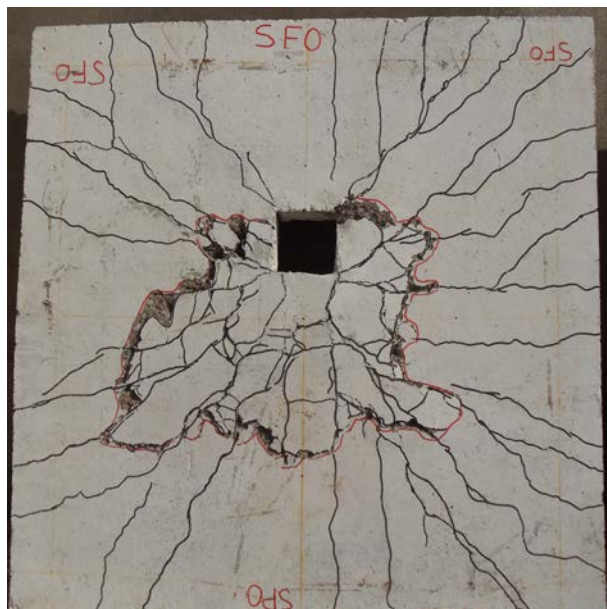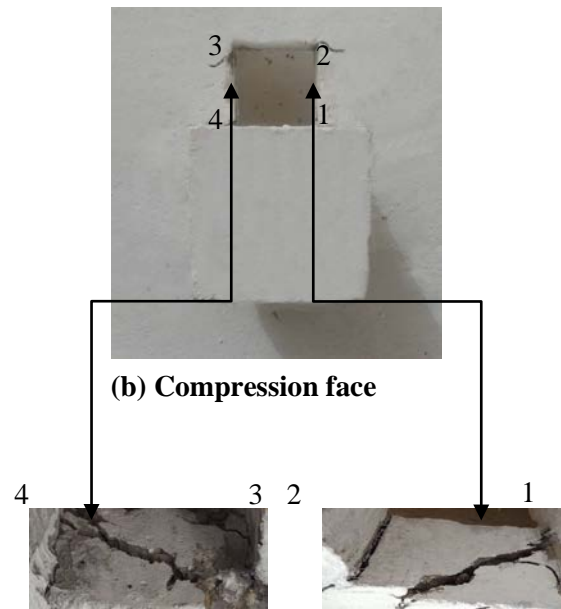
(a) Tension face   (c) Inside the opening

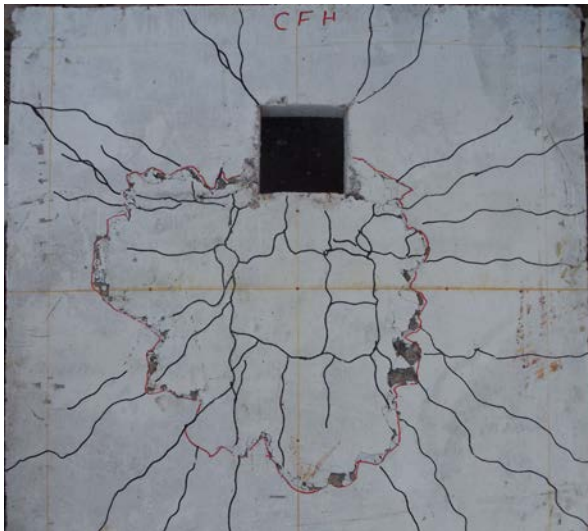**Fig.6: Cracks Pattern for Specimen SF0 (100×100 mm Opening Size) after Failure.**

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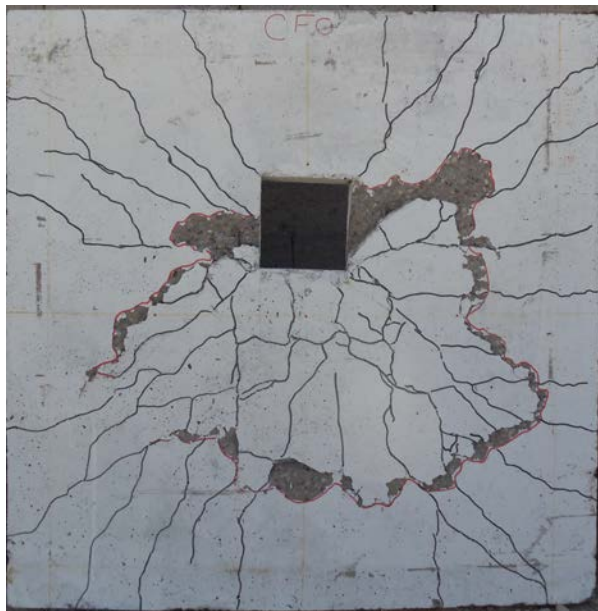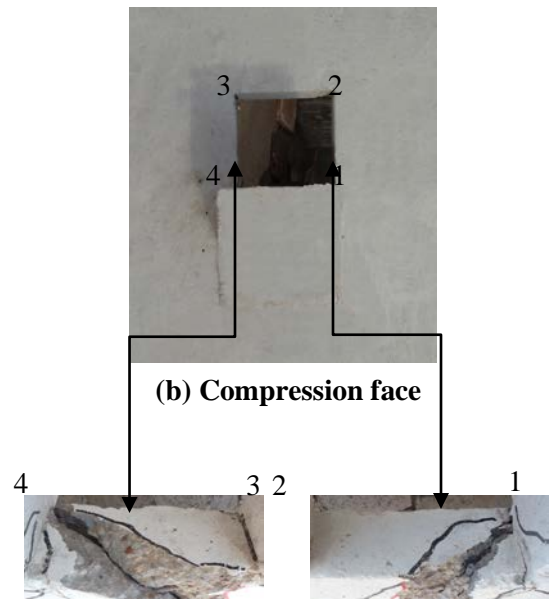
(a) Tension face

(b) Compression face

(c) Inside the opening

Fig.7: Cracks Pattern for Specimen CF0 (150×150 mm Opening Size) after Failure.
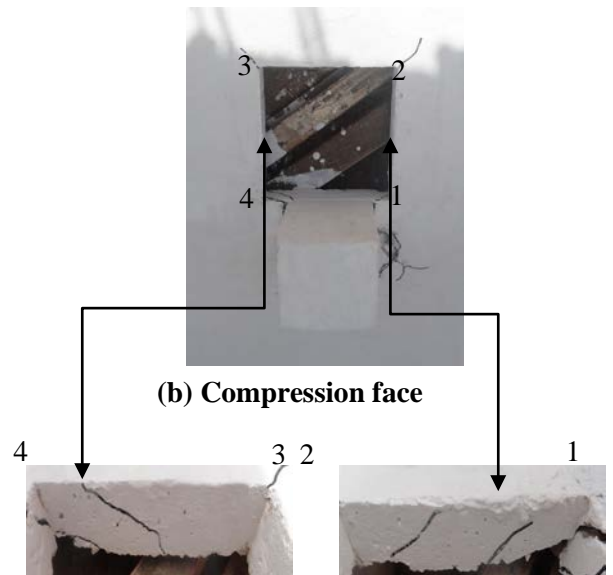
(a) Tension face

(b) Compression face

(c) Inside the opening

Fig.8: Cracks Pattern for Specimen LF0 (225×225 mm Opening Size) after failure.

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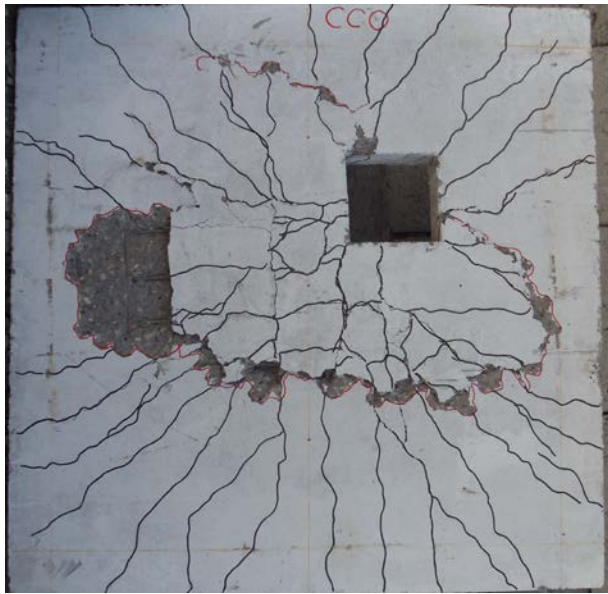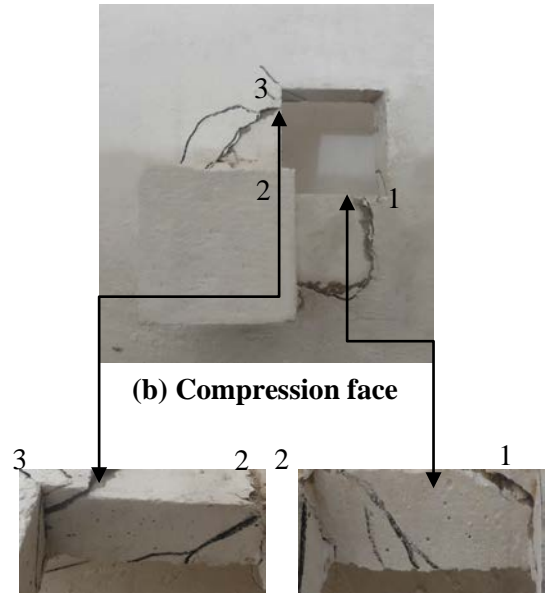
(a) Tension face

(b) Compression face

(c) Inside the opening

Fig.9:Cracks Pattern for Specimen CC0 (150×150 mm Opening Size) after Failure.

(a) Tension face
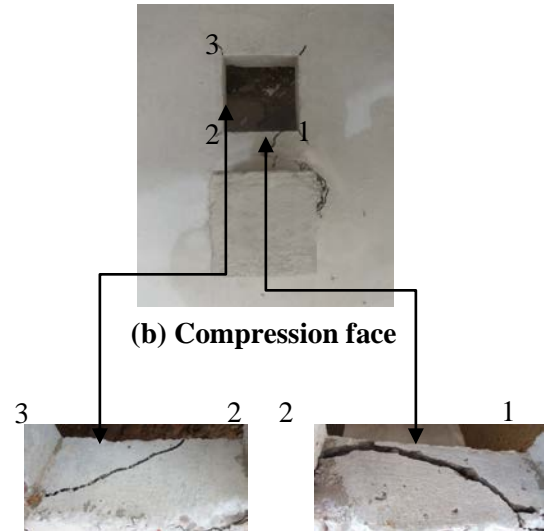
(b) Compression face

(c) Inside the opening

Fig.10: Cracks Pattern for Specimen CF1 (150×150 mm Opening Size) after Failure.
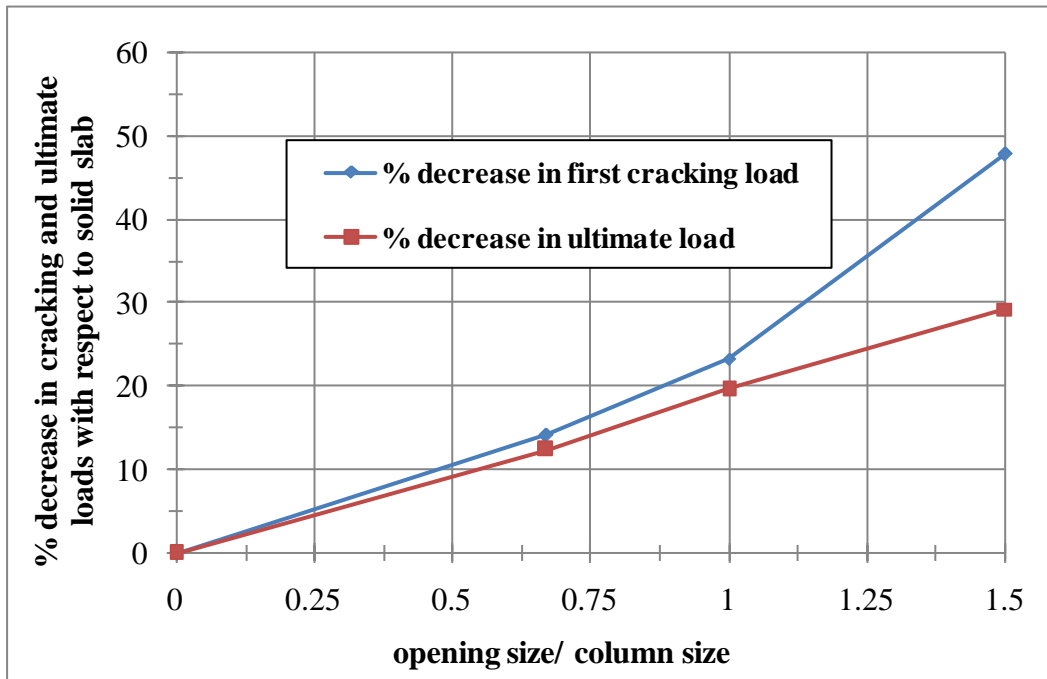
Fig. 11: Effect of Increasing (Opening Size/ Column Size) on the First Cracking and Ultimate Loads of the Specimens
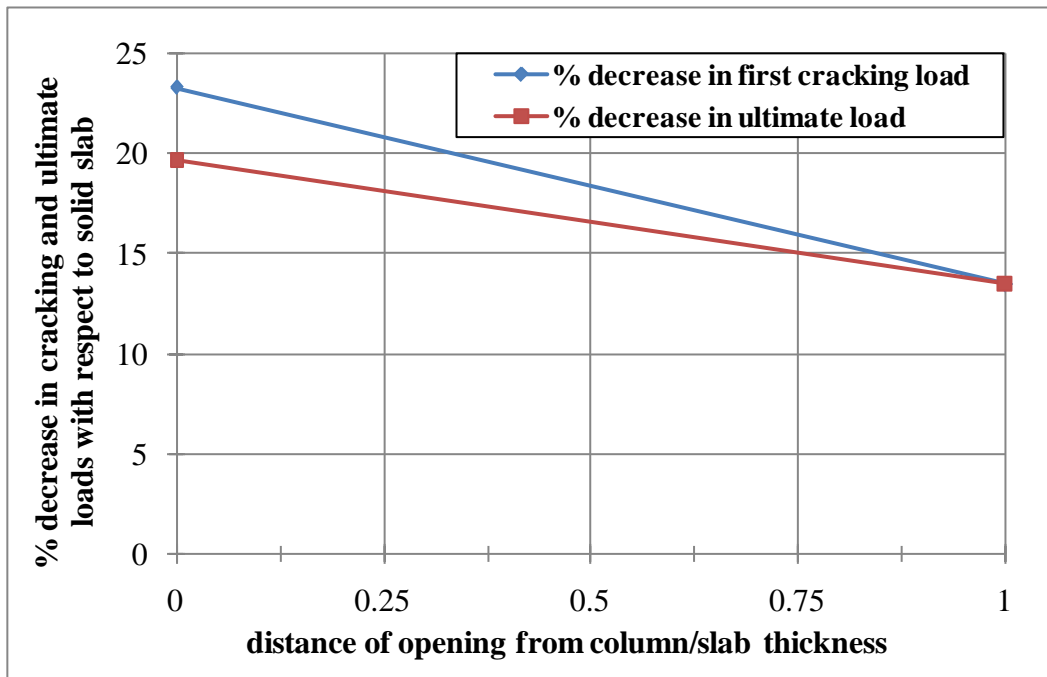
Fig. 12: Effect of Increasing (Distance of Opening from Column/ SlabThickness) On the First Cracking and Ultimate Loads of the Specimens
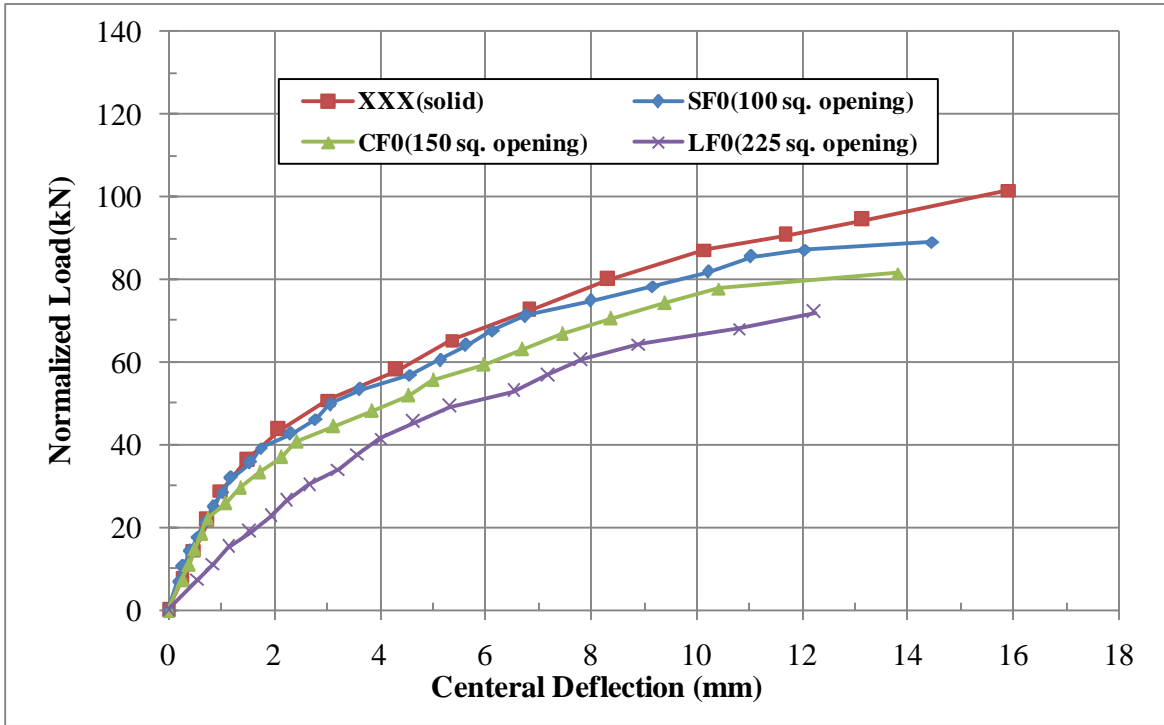
Fig. 13: Influence of the Size of Opening on the Normalized Load-Central Deflection Behavior of Specimens
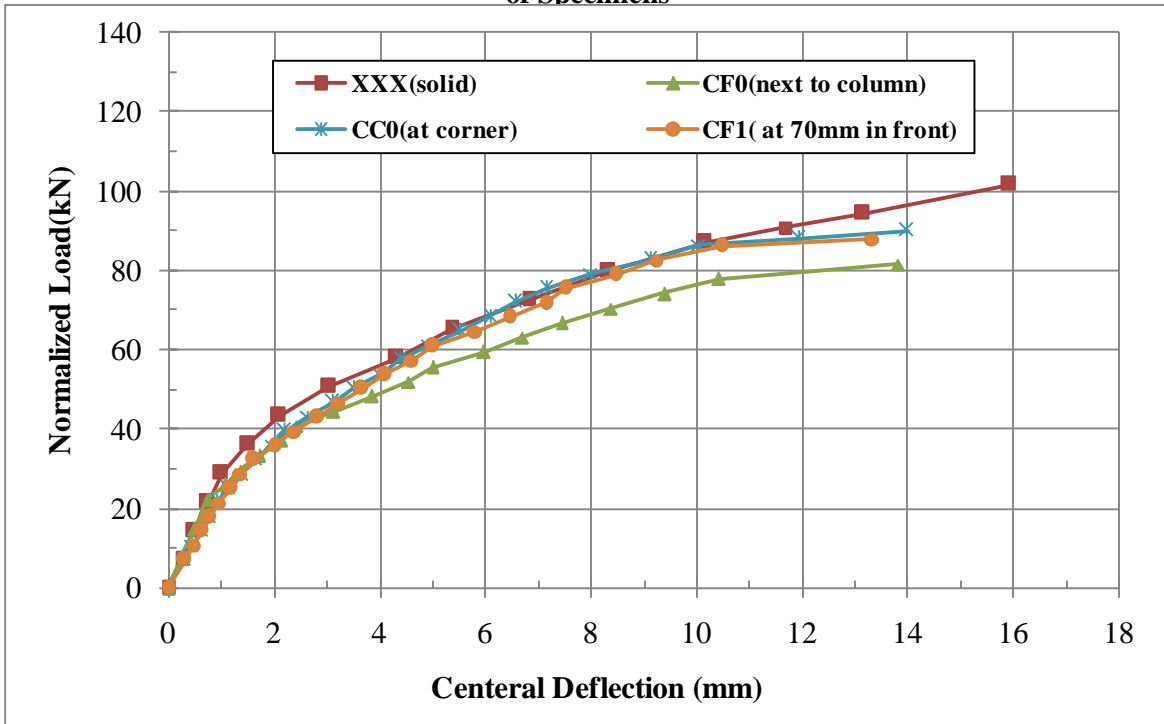
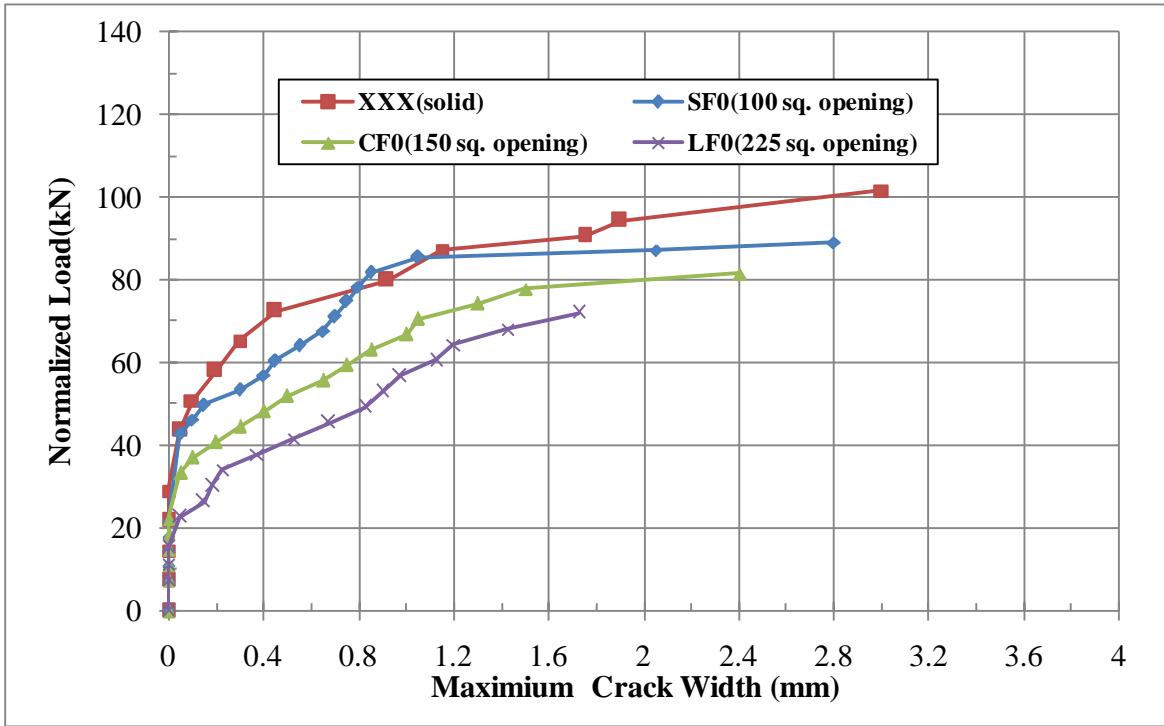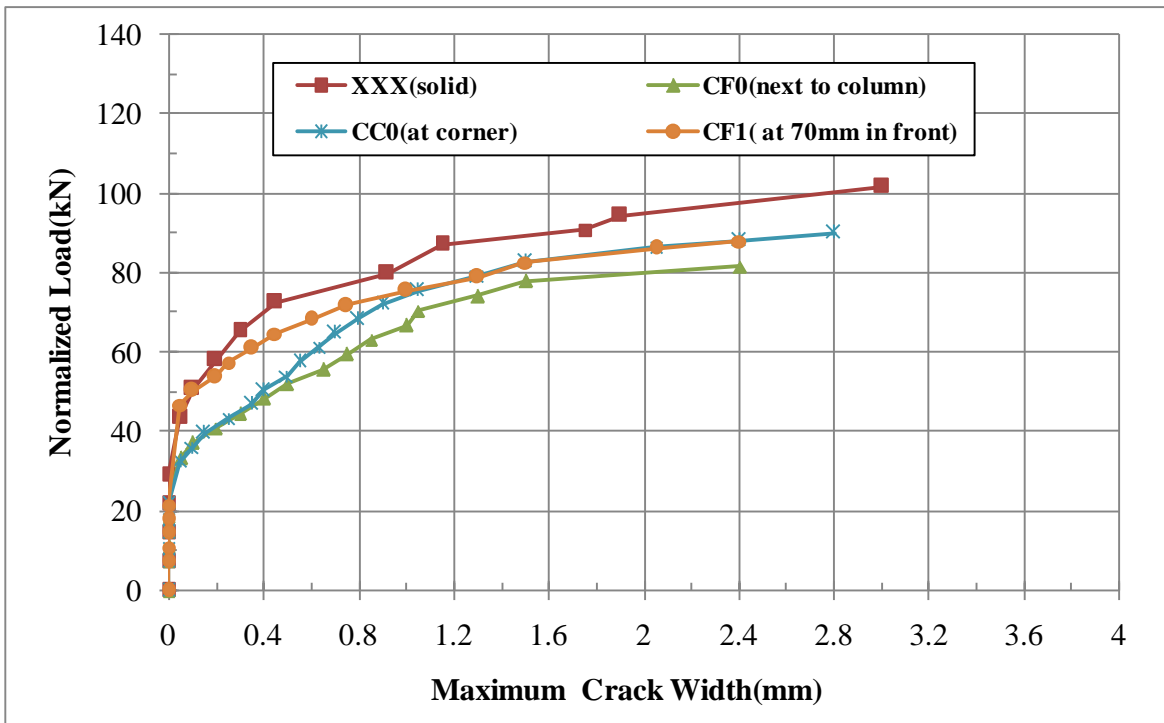**Fig. 14: Influence of the Location of Opening on the Normalized Load-Central Deflection Behavior of Specimens**

Fig. 15: Influence of the Size of Opening on the Cracking Behavior of Specimens

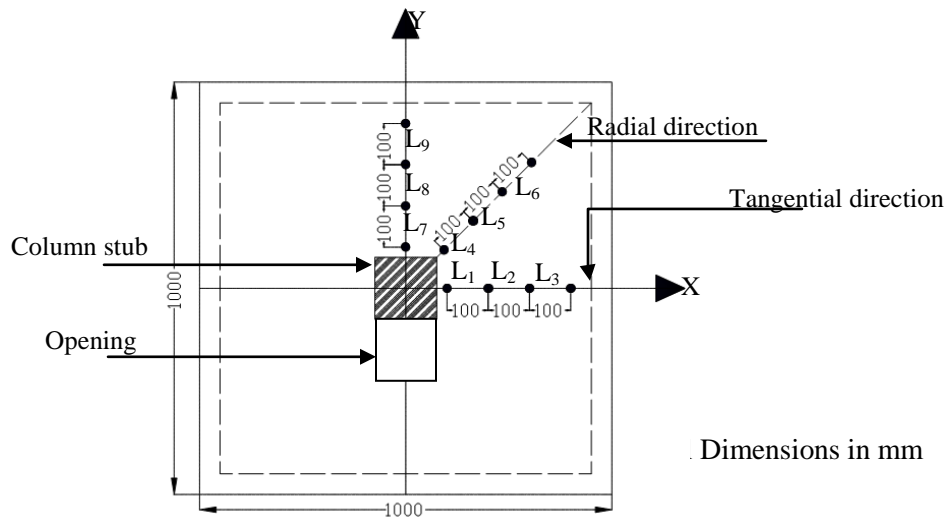**Fig. 16: Influence of the Location of Opening on the Cracking Behavior of Specimens**

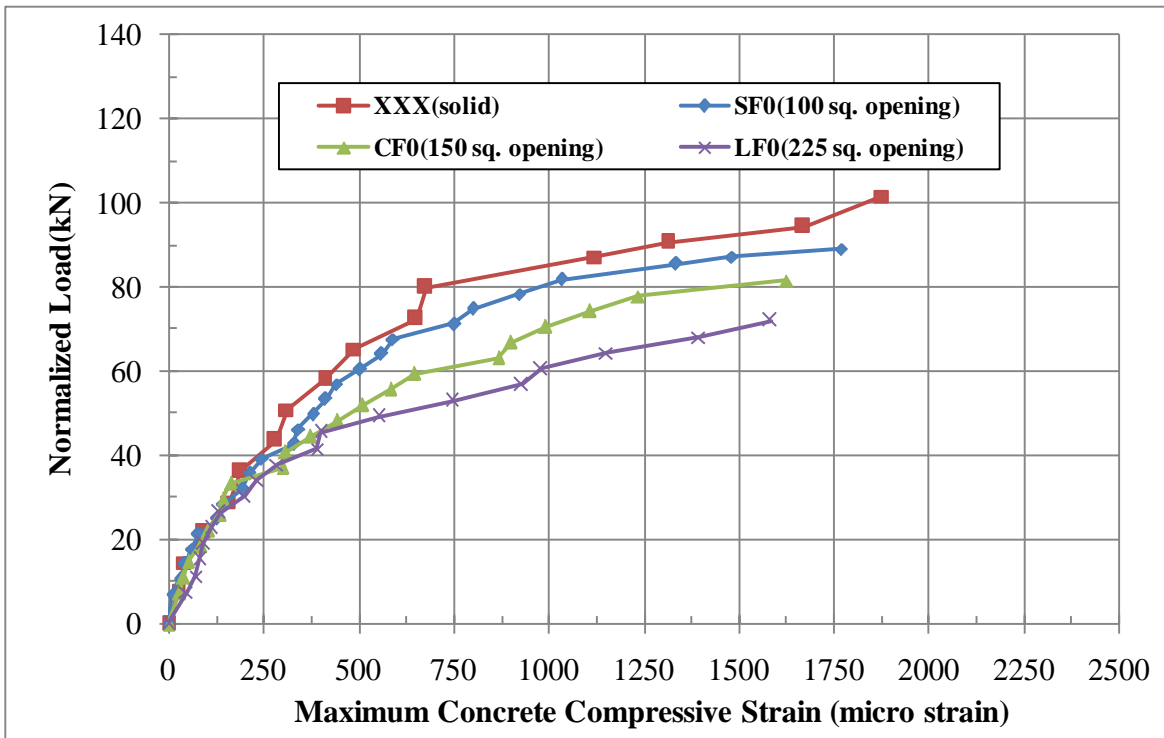**Fig.17: Demec Points Locations and Direction**

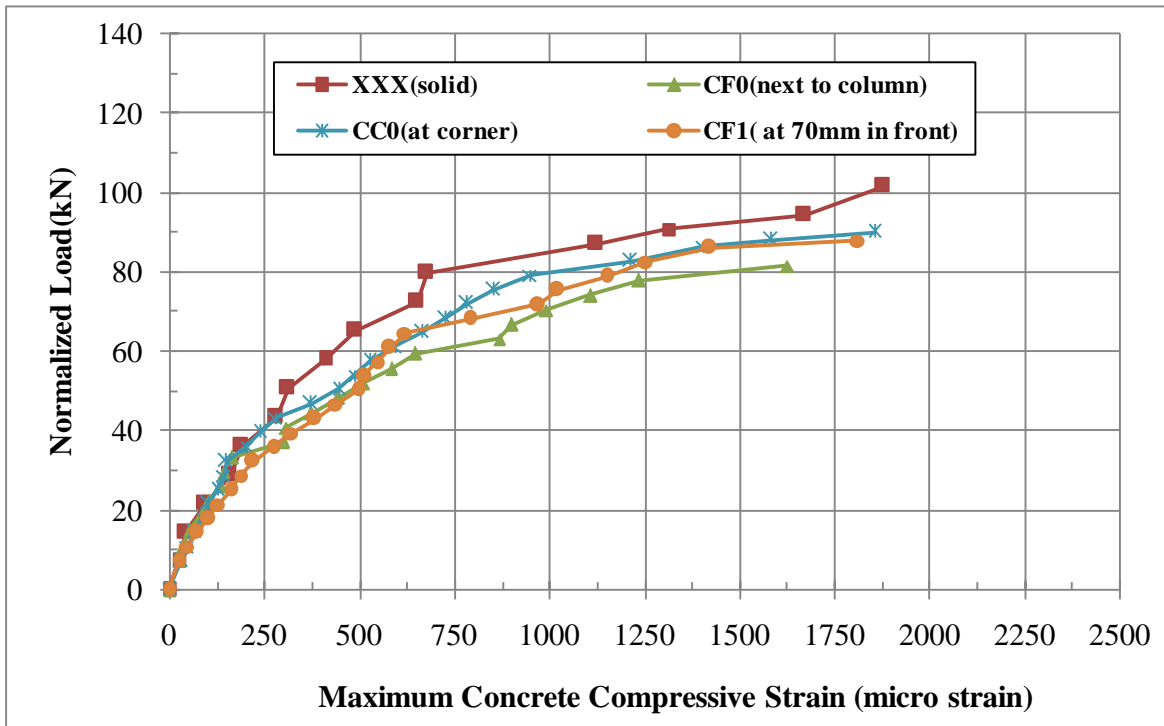**Fig. 18: Influence of the Size of Opening on the Maximum Concrete Compressive Strain**

Fig. 19: Influence of the Location of Opening on the Maximum Concrete Compressive Strain