EFFECT OF OPENIINGS WITH OR WITHOUT STRENGHENING ON PUNCHING SHEAR STRENGTH FOR REINFORCED CONCRETE FLAT PLATES

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ABSTRACT

Reinforced concrete slabs with openings are usually designed with help of traditional rules proposed by building codes. Such methods introduce limitations concerning size, location of openings and magnitude of applied loads. Furthermore, there are some traditional approaches to strengthen reinforced concrete slabs with openings which can be either cumbersome or expensive. This paper studies variable locations of an opening with respect to a central column in reinforced concrete flat plates, and presents a good approach to strengthen this opening by using steel plates.

Nine reinforced concrete flat plates are cast with dimensions (length, width and thickness) equal to (850, 470 and 50) mm) using a single concrete mix with average compressive strength (f_{cu}) equals 30 MPa. Each slab contains a square cross-section opening (side length =75 mm) and supported by a central square cross-section column (side length =75 mm). The variables of this study are: the type of opening (with or without strengthening) and the clear distance between the opening and the column which takes the values (0.0d, 2d, 4.5d and 7d), where d is the effective depth. The specimens are tested over a simply supported span at four edges.

The test results show that, the ultimate load reaches the maximum value for slab without opening while this load reaches the minimum value for slab with a non-strengthening opening and lies in the pattern of the failure zone (where the clear distance between the column and the opening equals 4.5d).

When a comparison is made between the test results ,it is concluded that ;strengthening the slab opening with steel plates causes increasing in the ultimate load by (19.44 ,19.51 ,35.13 and 13.46) % for the specimens (0.0d ,2d ,4.5d and 7d) respectively.

KEY WORD: Punching Shear, Flat Plate, Slab with Opening.

تأثير الفتحات مع أو بدون تقويه على مقاومة القص الثاقب لبلاطات خرسانية مستوية مسلحه

الخلاصة:

السقوف الخرسانيه المسلحة والحاوية على فتحات تصمم عادة بمساعدة القواعد التقليدية المقترحة من قبل انظمة (كودات) البناء .هذه الطرق تقدم حدود بخصوص حجم الفتحات ، موقع الفتحات وقيم الأحمال المسلطة.كذلك فان هنالك بعض الطرق التقليدية لتقوية السقوف الخرسانيه المسلحة ذات الفتحات وهذه الطرق أما متعبه أو مكلفه.هذا البحث يدرس مواقع متغيره لفتحه بالنسبة لعمود محوري لبلاطات خرسانيه مسلحه مستوية ،و يقدم طريقه جيده لتقوية تلك الفتحة باستخدام صفائح حديديه. تتضمن الدراسة صب تسعه نماذج من البلاطات الخرسانيه المسلحة بأبعاد (الطول ،العرض والسمك) مساوية إلى (850، 470 و 50) ملم ، كل سقف يحتوي فتحه ذات مقطع مربع (طول الضلع =75 ملم) ،باستخدام خلطه خرسانيه واحده بمعدل مقاومه انضغاط مساوية إلى 30 ميكا باسكال ،البلاطة مسنده بواسطة عمود محوري ذو مقطع مربع (طول ضلعه = 75 ملم) . متغيرات هذه الدراسة هي :نوع ألفتحه (

مع أو بدون تقويه) و المسافة الصافية بين العمود والفتحة والتي أخذت القيم التالية (0 ، 2، 4.5 و 7) من العمق الفعال .تم فحص النماذج على فضاء بسيط الإسناد من الجوانب الاربعه . نتائج الفحص بينت أن حمل الفشل وصل أعلى قيمه له في السقف الغير حاوي على فتحه ،و وصل أدنى قيمه له في السقف ذي الفتحة غير المقواة و واقعة على مسار حيز الفشل (عندما تكون المسافة الصافية بين العمود و الفتحة تساوي 4.5 من العمق الفعال).

عندما عملت مقارنه بين نتائج الفحوصات ،فقد تم استنتاج أن تقوية فتحات السقوف بصفائح حديديه يسبب زيادة في حمل الفشل بنسب (19.44 ،19.51 ،35.13 و 13.46) % للنماذج (0.0 ،2 ، 4.5 و 7) من العمق الفعال على التوالي .

INTRODUCTION

Openings in slabs are usually required for different purposes such as for fire protection pipes, plumbing, heat and ventilation ducts and air conditioning (Mota and Camara 2005). These openings can severely weaken the slab due to the discontinuity of both concrete and steel .There are some traditional approaches to strengthen opening including use of embedding reinforcing steel bars next to the opening, the addition of columns at the edges of openings and the good approach is the use of carbon fiber reinforced polymer (CFRP) systems, but this approach is expensive (Seliem and Sumner 2008).

In many cases only strengthening along opening edges is advised by adding reinforcing steel bars next to the opening .One practical method of reinforcement arrangement that consists in applying skew bars in opening corners. A big advantage in application of this method can be obtained since bars are situated perpendicular to the direction where the main crack is to appear (Rusinowsk 2005).

This study gives a clear understanding on the behavior and failure mechanisms of a proposed concrete slab with opening of different locations. Also gives a good approach to strengthen this opening with steel plates in section conforms to the opening. The output of this study will be beneficial to produce an efficient strengthening method to slab with opening .If the concept of strengthening using steel plates is commercially accepted ,thus a strengthening process can be conducted much easier with equally satisfactory solutions.

EXPERIMENTAL WORK

Experimental Program

The test program consists of fabricating and testing of nine reinforced concrete slabs with a central column and a single opening using a concrete mix with average cube compressive strength (f_{cu}) equal to (30 MPa). All slab specimens have the same dimensions (length, width and thickness) equal to (850, 470 and 50mm) and concrete cover of (15 mm); see Fig. 1. The variables investigated in this study are the type of opening (with or without strengthening) and the clear distance between the column and the opening in the slab specimen. Deformed welded wire fabric mesh (WWF) with (6mm) diameter and (75mm) c/c spacing each way are used as flexural reinforcement placed in tension faces. The average yield strength (f_y) of deformed wires is (438MPa).The specimens are divided into two groups, each of them includes four specimens, the specimens of the first group are with non strengthening openings while the specimens of second group are with strengthening openings, the ninth specimen is cast without opening and considered as a reference. Table 1 shows the detail of the specimens. All specimens are tested over a simply supported span at four sides using a steel frame made for this purpose.

MATERIALS

The materials used in manufacturing the test specimens are reported and presented in Table 2 with descriptions; the tests of materials are presented in Tables 3, 4 and 5 and the concrete mix proportions are reported and presented in Table 6.

Details of Moulds and Openings

Steel moulds are used for casting control specimens while wooden moulds are used for casting slab specimens, the central column of slab is fabricated by using a hollow wooden square cross-section box (clear side length =75mm) and a solid wooden box is used to fabricate the opening in specimens of group A, Fig. 2a shows details of mould of group A and Fig. 2b shows the reinforcement details of the column.

The same moulds are used to fabricate specimens of group B, but the strengthening of opening is made by using steel plates in square cross-section (side length =75 mm, thickness of plates =3mm). Bond between steel plates and concrete is obtained by using bolts welded to the steel plates (two bolts of diameter 17 mm in each side) as shown in Fig.3.

Mixing, Casting, Compacting and Curing Procedure

The mixing procedure was as follows:-

- Before mixing, all quantities are weighted and packed in clean containers.
- Saturated surfaces dry crushed gravel and dry sand are added to the rotary drum mixer of ($0.18m^3$) volume capacity and mixed for several minutes.
- The cement is then added to the mixer, and water is added gradually to the mix. The total mixing time is (8-10 minutes).
- The moulds are coated with oil before putting the reinforcing bar, or casting the control specimens.
- Before placing the concrete in the mould, steel reinforcement is placed in the mould and the specimen is cast in two layers. Then, column is cast continuously (monolithically) with slab. Specimens were compacted by a table vibrator with a compaction time (2minutes) for each layer; some of these procedures are explained in Fig.4. After casting, the slab specimens and control specimens are covered with polythene sheets and after (24 hours) they are stripped of the moulds and placed in water for other (27days) and then tested.

Test Measurement and Instrumentation

A hydraulic universal testing machine (MFL system) is used to test the specimens as well as control specimens. Central deflection has been measured by means of (0.01mm) accuracy dial gauge (ELE type) and (30mm) capacity. The dial gauges are placed underneath the bottom face of each span at mid, Fig. 5 shows the test instrumentation. All tests are made in the Laboratory of Structures in Al-Mustansiriya University, College of Engineering.

RESULTS AND DISCUSSIONS

Engineering Properties of Hardened Concrete

Control specimens ,which contain four standard cylinders, three cubes and one standard prism with each slab specimen ,are tested at age of 28 days to determine the engineering properties of hardened concrete ,which include concrete compressive strength, modulus of elasticity E_c , splitting tensile strength $f`_{sp}$ and modulus of rupture f_r. Table 7 shows the engineering properties.

SLAB SPECIMENS

In this study, eight opened slabs are tested in addition to another slab without opening (reference). These slabs are identical in size and ratio of steel reinforcement, but different in the type of opening and in the clear distance between the column and the opening in the slab specimen. According to these variables, ultimate loads, crack patterns as well as shapes of failure are different from each other.

Crack Pattern

The test results of cracking and ultimate loads are reported and presented in Table 8. When load is applied to these slab specimens, the first cracks form at about (15.5-20.4) % of the ultimate load for the slab specimens. At ultimate load, punching shear failure occurs suddenly for all specimens

The first crack appears around the sides of the column on the tension face of the slab and other cracks form at the central region of the slab. By increasing the load, these cracks widen and increase in number. At ultimate load, punching shear failure occurs suddenly for all slabs. Fig. 6 illustrates crack patterns and failure modes of specimens. From Fig. 6 it is evident that the capillary cracks appear in the tensile face of the slabs when the moment generated from the applied load reaches to the crack moment. Also it is clear that the punching cracks for the specimens of group B do not enclose around themselves because the presence of steel plates strengthen the area around the opening.

Load-Deflection Behavior

The deflection results of all specimens are illustrated in Table 9. The test results show that, the deflection at ultimate load increases as the ultimate load increases (specimens $A_{4,}$ $_{B4}$ and R have maximum deflection due to maximum ultimate load). Also Fig. 7 and Fig. 8 show the load-deflection relationships of the slabs. From these figures, it is observed that the specimens have a convergent load-deflection behavior because of the size of specimens which is rather small.

Ultimate Loads

Ultimate load capacity for punching failure is illustrated in Table 8.The test results show that:-

- The ultimate load reaches the maximum value for the specimen (R) of no opening
- Strengthening the slab opening with steel plates causes increasing in the ultimate load by (19.44 ,19.51 ,35.13 and 13.46)% for the specimens (0d ,2d ,4.5d and 7d) respectively.
- The ultimate load is about (51.79, 59.00, 42.86 and 84) % and about (64.30, 73.21, 66.07 and 96.43) % of the ultimate load of the reference (R) for the specimens (A_1 – A_4) and for the specimens (B_1 –B_4) respectively.
- The ultimate loads increase as the clear distance between the column and the opening is increased , except specimens A_3 and B_3 because the opening lies in the pattern of the failure zone (where the clear distance between the column and the opening equals 4.5d) (Al-Hafiz 2009). See Fig. 9.

Area of Failure Zone

The areas and perimeters of the punching failure zones are measured for the specimens (A_1, A_2, A_4 and R) only because the opening of the specimen A_3 leis in the pattern of the failure zone where the clear distance between the column and the opening equals 4.5d (Al-Hafiz 2009) (i.e. the failure zone does not enclose around itself).Also the areas of the punching failure zones of specimens of group B do not be measured because the steel plates strengthen the area around the opening (also the failure zones do not enclose around itself), see Fig. 6.

From Table 10, it is concluded that the area of failure zone of the specimen A_2 is greater than that of the specimen A_1 by about 56% (i.e. the area of failure zone increase as the clear distance between the column and the opening is increased), while the area of failure zone of A_4 is smaller than that of A_2 by about 10% because the position of the column is out of the area of the failure zone.

Comparison of Experimental Results with ACI-318 Code (2008) and BS 8110 (1997)

Many codes and researchers have presented different formulas for predicting punching shear strength of slabs based on their understanding of punching behavior, the ACI-318 Code (2008) is considered in this study and compared with its results. Punching strength is predicted by considering the effect of opening on the value of b_o according to the item 11.12.5 of chapter eleven of ACI 318 Code; see Table 11 and Fig. 10.

From Fig. 10, it is evident that the punching shear strength v_u increases as the clear distance between the column and the opening is increased because of the decreasing of the effect of this distance on the value of b_0 as it is increased. Also it is clear that the punching shear strengths for all slabs are safe (the experimental results are larger than the computed results) except the specimen A3 because the opening lies in the pattern of failure zone as mentioned before.

BS 8110-1 (1997) is also considered in this study, punching strength is calculated by considering the effect of opening on the value of u (perimeter of failure zone) according to the item 3.7.7 of section three of the BS, see Table 12.

From Table 12 it is clear that the punching shear strength v_u increases as the clear distance between the column and the opening is increased for the same reason above.

f_{cu}=30MPa

When the clear distance between the column and the opening is greater than 6d, the opening has no effect on the value of u according to BS 8110-1.

CONCLUSIONS

Depending on the test results of this study, the following conclusions are obtained:-

- The first cracks form at about (15.5-20.4) % of the ultimate load for the slab specimens.
- At ultimate load, punching shear failure occurs suddenly for all specimens
- The ultimate load reaches the maximum value for slab without opening while this load reaches the minimum value for slab with a non-strengthening opening and lies in the pattern of the failure zone (where the clear distance between the column and the opening equals 4.5d) .
- The ultimate loads increase as the clear distance between the column and the opening is

increased except specimens with opening lies in the pattern of the failure zone (where the clear distance between the column and the opening equals 4.5d) which have smaller ultimate load.

- Strengthening the slab opening with steel plates causes increasing in the ultimate load by (19.44 ,19.51 ,35.13 and 13.46) % for the specimens (0.0d ,2d ,4.5d and 7d) respectively.
- The punching shear strength v_u according to both ACI 318 Code and BS 8110-1 increases

as the clear distance between the column and the opening is increased.

NOTATION

b_o : perimeter of failure zone;

d: Effective depth of slab;
$f`_c$: Ultimate cylinder compressive strength;
f_{cu}: Ultimate cubic compressive strength
f_y : Yield tensile strength;
f_u: Ultimate tensile strength;
X: Clear Distance between the column and the opening.

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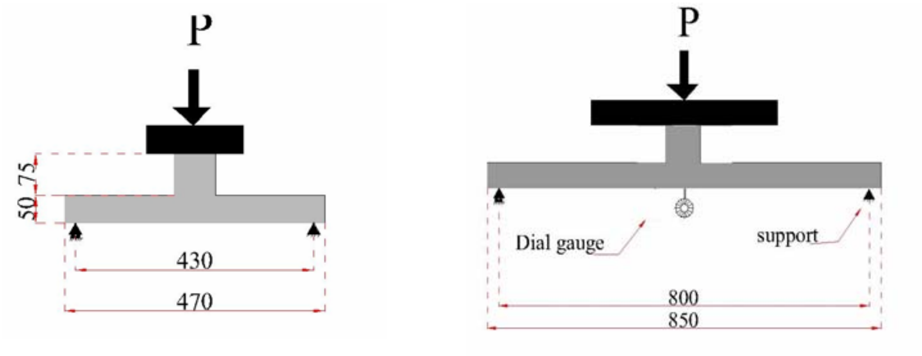
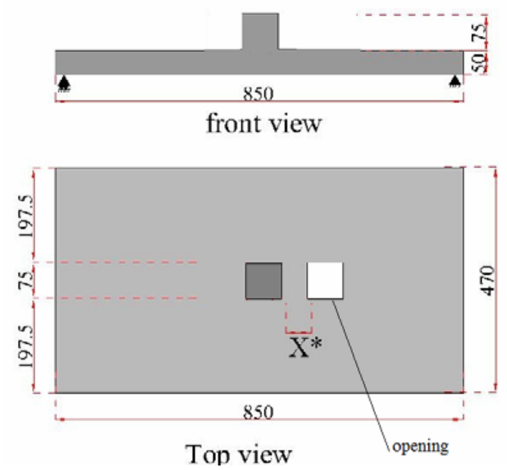
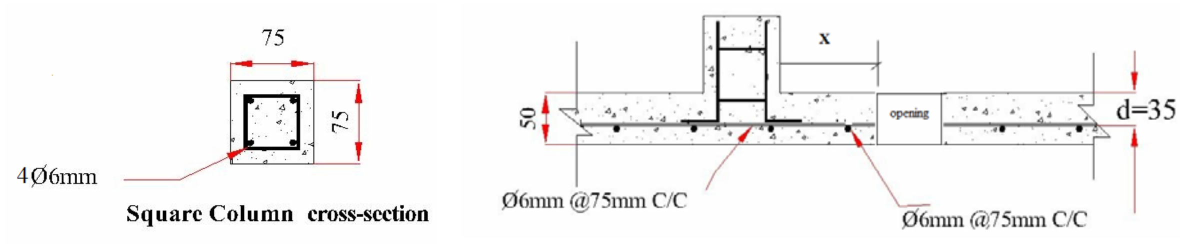


a) side view **b) front view**

Details of Slab Specimen Test and its Loading Arrangement



Details of Slab Dimensions.



Details of specimen cross-section

Fig. 1: Details of Slab Specimen.

Notes: All dimensions are in mm.
(*)X is a variable distance; its values are given in Table 1.

Table 1: Dimension Details of Tested Slabs

Group	Designation	Column side length (mm)	Opening side length (mm)	Clear distance between Column and opening (X)
A	A_1	75×75	75×75	0.0 d*
	A_2			2 d
	A_3			4.5 d
	A_4			7 d
B	B_1			0 d
	B_2			2 d
	B_3			4.5 d
	B_4			7 d
Reference	R			Without opening

(*) d (the effective depth) = 35 mm.

Table 2: Description of Construction Materials

Material	Descriptions
Cement	Ordinary Portland Cement (Type I), properties of this cement are shown in Tables 3a and 3b, which comply with the Iraqi Standard Specification No.5/1984 Requirements.
Sand	Natural sand from Al-Ukhaider region with maximum size of (4.75mm). The grading of the fine aggregate is shown in Table 4, which complies with the Iraqi Standard Specification No.45/1984.
Gravel	Crushed gravel with maximum size of (10mm) from Al-Nibaee area. The grading of the coarse aggregate is shown in Table 5, which complies with the Iraqi Standard Specification No.45/1984.
Reinforcing Bars	Deformed welded wire fabric mesh (WWF) with (6mm) diameter and (75mm) c/c spacing each way are used as flexural reinforcement placed in tension faces. The average yield strength (f_y) is (438MPa) and the average ultimate strength (f_u) is (580MPa).
Water	Tap water.

Table 3a:

chemical properties of cement #.

#All chemical tests are made in the National Center for Construction Laboratories and Researches

Oxides		%	IQS 5:1984 Limits
Calcium Oxide	Ca O	63.19	
Silicon Oxides	SiO_2	20.06	
Aluminum Oxides	Al_2O_3	5.28	
Ferric Oxides	Fe_2O_3	4.10	
Magnesium Oxides	Mg O	2.28	5.00 max.
Sulfur Trioxides	SO_3	1.98	2.80 max.
Loss on Ignition	L.O.I	2.45	4.00 max.
Insoluble Residue	I.R	0.47	1.50 max.
Lime Saturation Factor	L.S.F	0.94	0.66-1.02
Bogue's Potential Compound		**%**	
Tricalicium Silica	C_3S	57.11	
Dicalicium Silica	C_2S	16.23	
Tricalicium Aluminates	C_3A	3.29	
Tetra Calcium Aluminaferite	C_4AF	13.23	

Table 3b:

Physical Properties of Cement#

Physical Properties	Test Result	IQS 5:1984 limits
Fineness: Specific surface, Blaine(cm^2/gm)	3329	2300 min.
Soundness, Autoclave %	0.19	0.8 max.
Setting time ,Vicat's method:- Initial (min) Final (min)	 175 255	 45 min. 10 max.
Compressive strength of cement (MPa) 3 day 7days	 32.4 40.5	 15 min. 23 min.

#All physical tests are made in the National Center for Construction Laboratories and Researches

Table 4: Grading of Fine aggregate (Sand)#

No.	Sieve (mm)	%Passing	
		Fine aggregate %	IQS 45:1984Zone(2)
1	5	100	90-100
2	2.36	83.75	75-100
3	1.18	63.84	55-90
4	0.6	35.84	35-59
5	0.3	5.84	8-30
6	0.15	0.64	0-10

All tests are made in the Laboratory of Materials in Al-Mustansiriya University, College of Engineering.

Table 5 : Grading of Coarse aggregate (Gravel)#

No.	Sieve (mm)	%Passing	
		Coarse aggregate %	IQS 45:1984 size (5-14)mm
1	14	100	90-100
2	10	74.5	50-85
3	5	3.5	0-10
4	2.36	0	-

All tests are made in the Laboratory of Materials in Al-Mustansiriya University, College of Engineering.

Table 6: Mix Proportions by Weight

Mix proportions	W/C ratio	Water (L/m^3)	Cement (kg/m^3)	Sand (kg/m^3)	Gravel (kg/m^3)
1:1.5:3	0.45	225	500	750	1500

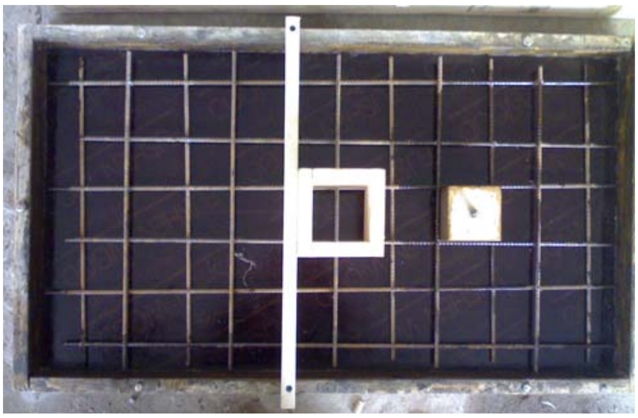


Fig. 2a: Details of mould of group A

Fig. 2b: Reinforcement of column

Fig. 3: Details of mould of group B

Fig.4: Casting Procedure

Fig. 5: Test Instrumentation.

Table 7: Engineering Properties of Hardened Concrete

Specimen	Average compressive strength f'_c (MPa)	Average compressive strength f_{cu} (MPa)	Measured Static Modulus of Elasticity GPa	Measured Splitting Tensile Strength(f'_{sp}) (MPa)	Measured Modulus of Rupture f_r (MPa)
A_1	22.1	29.1	25.5	2.50	3.36
A_2	21.8	32.8	26.5	2.62	4.50
A_3	22.5	31.3	26.1	2.59	4.08
A_4	23.5	30.5	26.2	2.59	3.85
B_1	21.9	29.3	25.5	2.58	3.38
B_2	22.3	28.8	25.1	2.40	3.21
B_3	23.8	29.3	25.6	2.57	3.37
B_4	22.7	29	25.3	2.48	3.30
R	23.78	31.5	26.2	2.60	4.15

Table 8: First Crack and Ultimate Loads of Slabs

Group	Designation	Clear distance between column and opening		f_{cu} (MPa)	First crack load (P_{cr}) (kN)	Ultimate Load (P_u) (kN)	$\frac{Pcr}{Pu}$ (%)
		(X) mm	X/d				
A	A_1	0	0	29.11	4.5	29	15.5
	A_2	70	2	32.8	5.5	33	16.6
	A_3	157.5	4.5	31.33	4	24	16.6
	A_4	245	7	29.33	8	47	17
B	B_1	0	0	28.88	6.5	36	18.1
	B_2	70	2	29.33	7.5	41	18.3
	B_3	157.5	4.5	32.22	6	37	16.2
	B_4	245	7	29.78	11	54	20.4
Reference	R	without opening		31.5	10	56	18

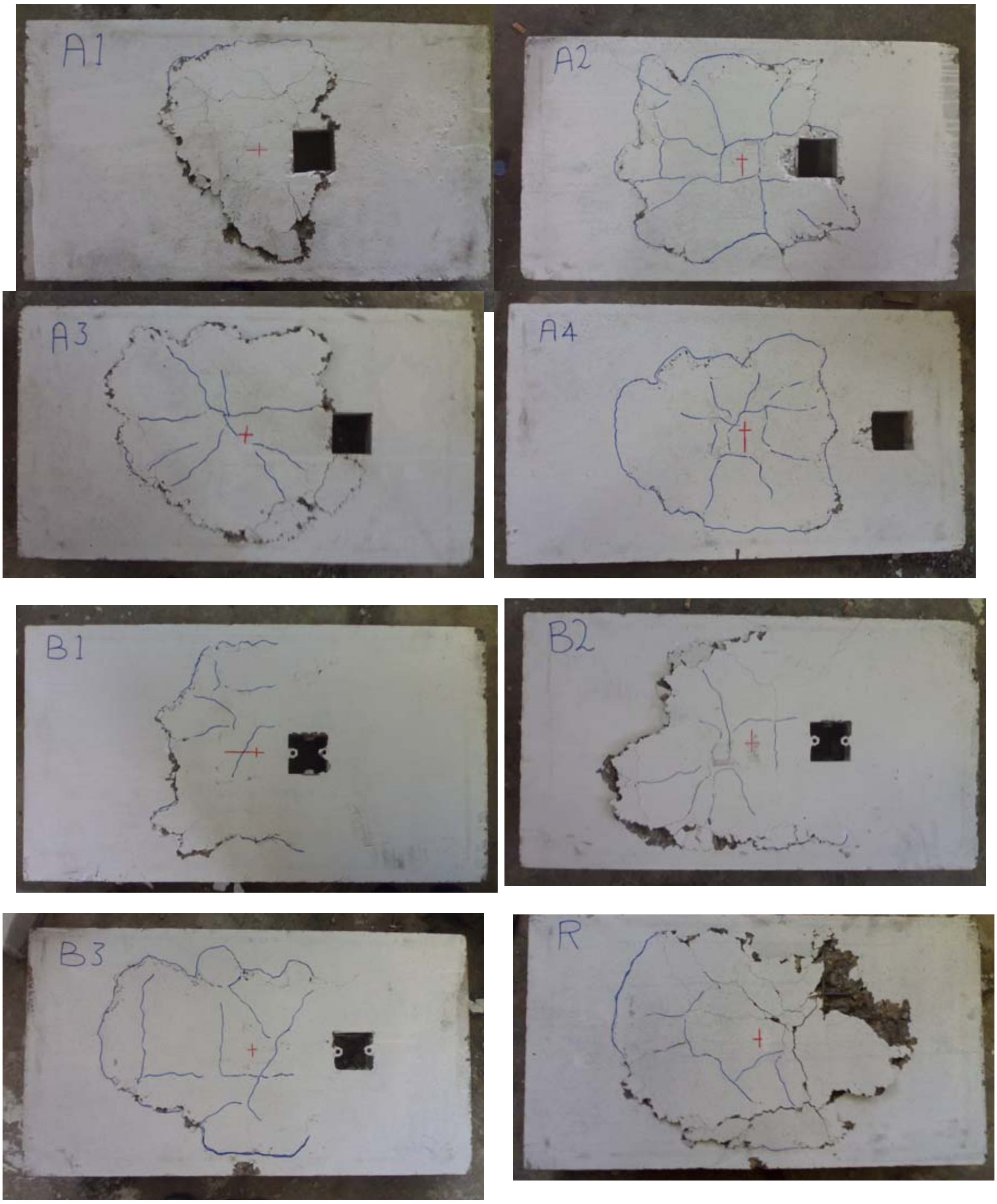
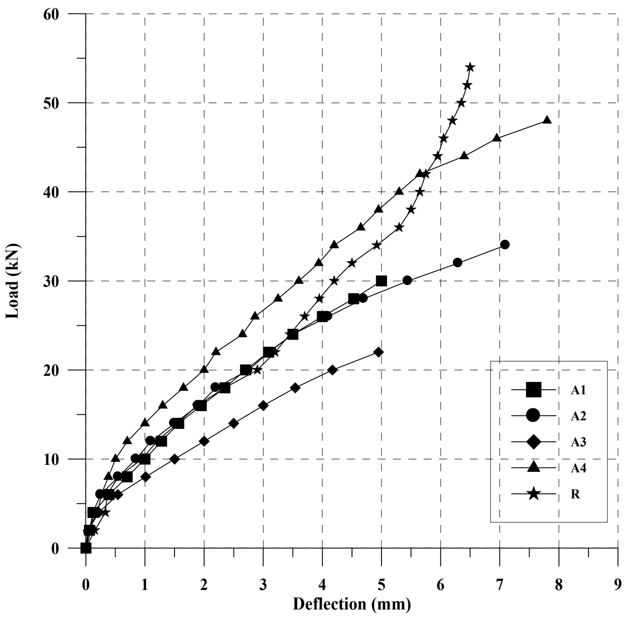


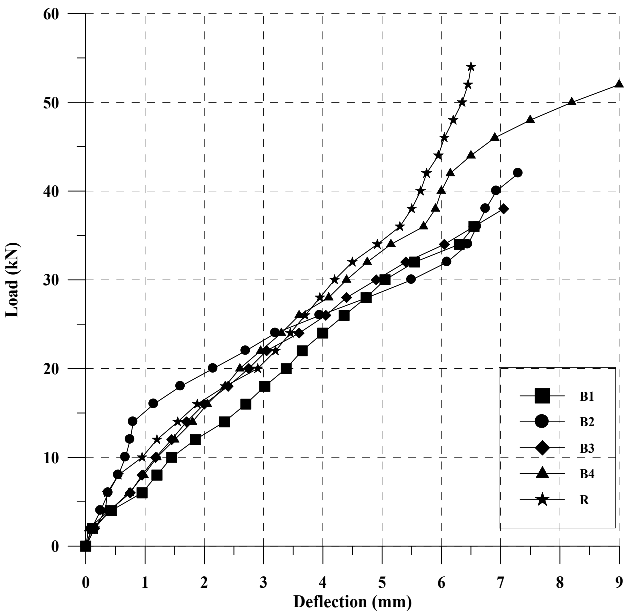
Fig. 6: Crack Patterns at a Bottom face of Slabs at Failure Stage.

Table 9: Load and Deflection Characteristics at First Crack and at Ultimate Loads

Group	Specimen	Deflection at first crack (mm)	Deflection at ultimate load (mm)
A	A_1	0.16	5
	A_2	0.2	7.1
	A_3	0.22	5
	A_4	0.38	7.8
B	B_1	0.98	6.55
	B_2	0.5	7.3
	B_3	0.75	7.05
	B_4	1.35	9
Reference	R	0.95	6.5



Group A



Group B

Fig. 7: Load-Deflection Relationship for groups A and B

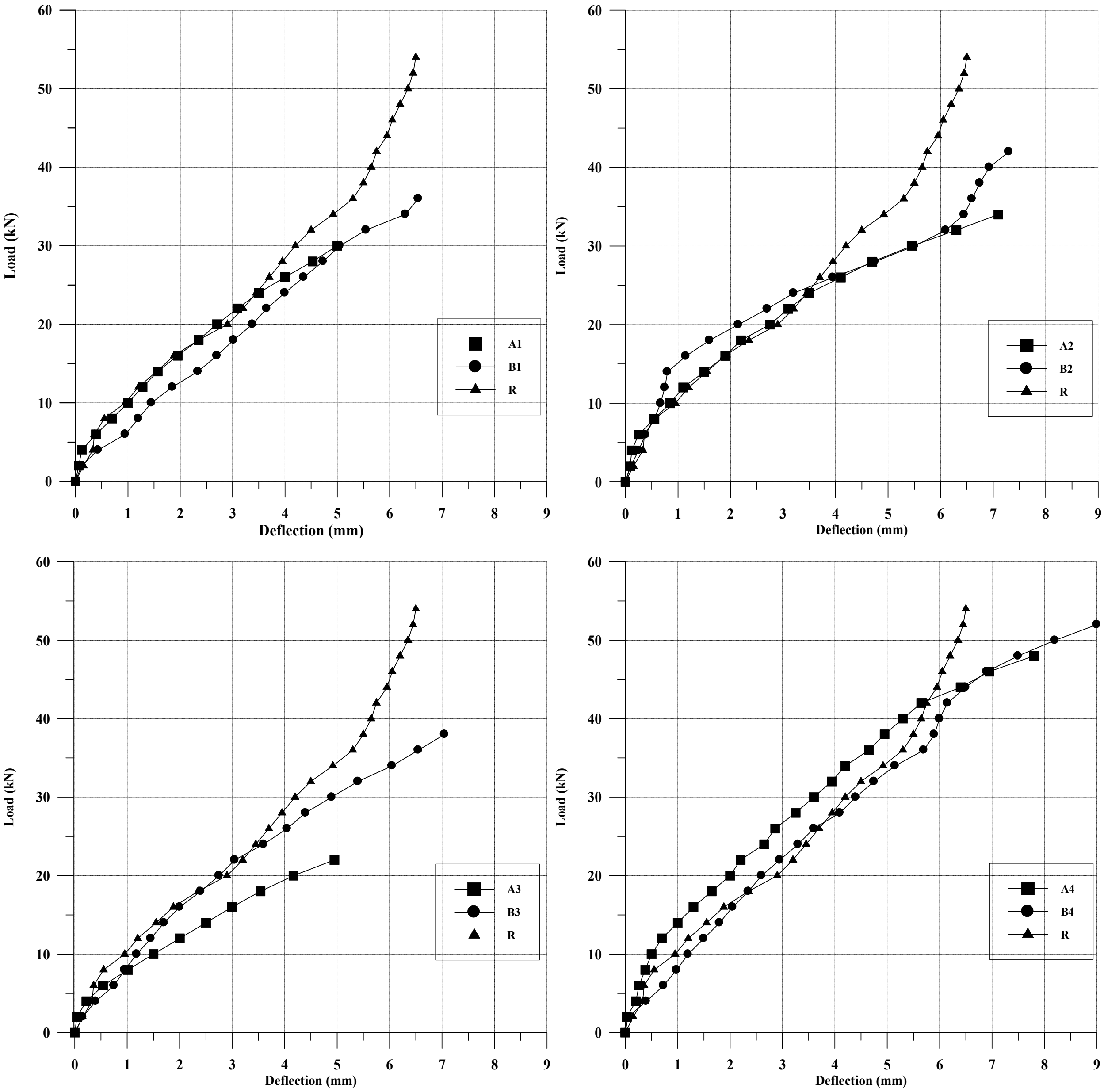


Fig. 8: Comparison of Load-Deflection Relationships between Group A and Group B

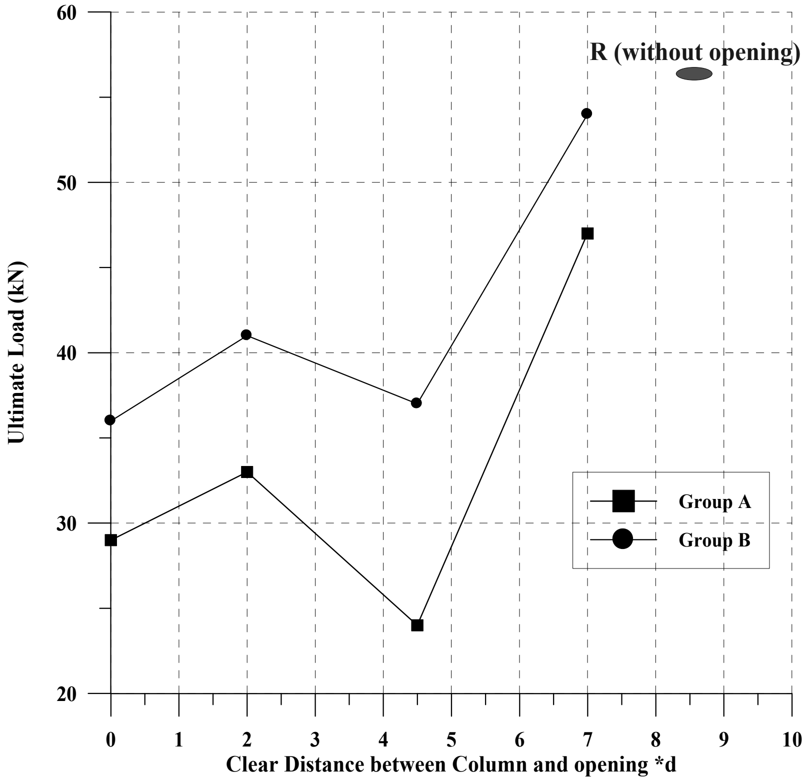


Fig.9: Ultimate Load – Clear Distance between column and opening relationship

Table 10: Area and Perimeter of the Failure Zone

Slab	Measured area (mm^2)	Measured perimeter (mm)
A_1	88702	1363
A_2	138283	1477
A_4	125637	1484
R	170016	1835

Table11: Punching Shear strength of Slabs according to ACI 318 Code

Specimen	$P_{u(EXP)}$ kN	$b_\circ$ (mm)	v_u (kN) using ACI Code $v_u = \frac{1}{3}\sqrt{f`_c}\, b_\circ\, d$ *
A_1	29	365	20.42
A_2	33	421	23.57
A_3	24	432	24.10
A_4	47	435	24.32
B_1	36	365	20.42
B_2	41	421	23.57
B_3	37	432	24.10
B_4	54	435	24.32
R	56	440	24.62

(*) $f`_c$=23 MPa

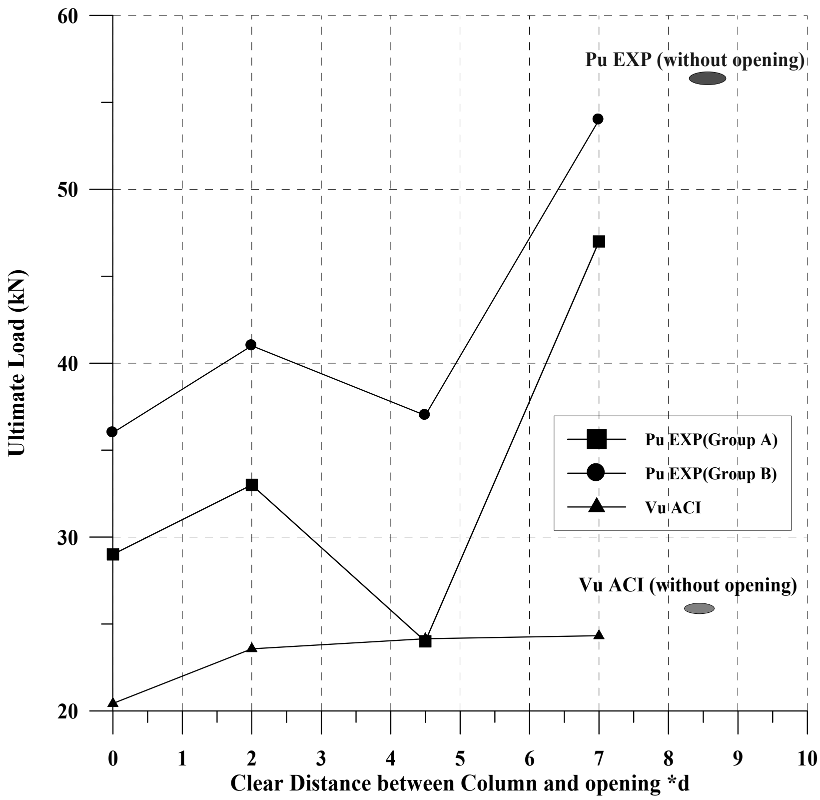


Fig. 10: Ultimate Load – Clear Distance between column and opening relationships

Table12: Punching Shear strength of Slabs according to BS 8110-1.

Specimen	$P_{u(EXP)}$ kN	u (mm)	v_u (kN) using BS $v_u=v_{ck}$ ud
A_1	29	540	29.90
A_2	33	657	36.38
A_3	24	685	38.00
A_4	47	720	39.87
B_1	36	540	29.9
B_2	41	657	36.38
B_3	37	685	37.00
B_4	54	720	39.87
R	56	720	39.87