EXPERMENTAL STUDY OF PUNCHING SHEAR FOR REINFORCED CONCRETE FLAT PLATE SLABS WITH COUPLED COLUMNS

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Abstract

This study is conducted to investigate the punching shear of reinforced concrete flat plate slabs supported by coupled columns; sixteen specimens with average cube compressive strength (f_{cu}) of (28 MPa) were tested.The slab specimens were made with (850x470x50mm) dimensions and concrete cover of (15 mm). The specimens were tested over a simply supported span (800 x 420mm) at four sides. The variables investigated in this study are the shape of column and the clear distance between columns of the slab specimen. The specimens are divided according to column shape into two groups, each group includes eight specimens.The first group (group A) has two square columns with cross sectional dimensions of (75x75mm) and height of (75mm) and column cross-sectional area equals to (5626mm). The clear distance between columns were varied from (2 mm) to (325 mm) (equals to 0.05d to 9.3d). While, the second group (group B) has two circular columns with (85mm) diameter and (75mm) height and column cross-sectional area equals to (5671)mm with variable clear distance between them from (2 mm) to (315 mm) (equals to 0.05d to 9d).

The test results showed that, the ultimate load reaches the maximum value when the distance between columns equal to (9.3d and 9d) for group (A) and (B) respectively; and decreases by (6.5 to 33.9%) and by (16.4 to 35.9%) of the maximum ultimate load when the clear distance between columns decreases by (7d to 0.05d) for group (A) and (B) respectively.

The test results show that when the clear distance between columns is in the range of (0.05d to 7d) ,the failure zone is separated as one zone ;while when the clear distance between columns is equal to (9.3d and 9d), the failure zone separates into two zones.

Key words: Punching, Shear, Flexural, flat plate, coupled, columns.

دراسة عملية للقص الثاقب للبلاطات الخرسانية المسلحة ذات اعمدة مزدوجة

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الخلاصة

اعدهذا البحث لدراسة القص الثاقب للبلاطات الخرسانية المسلحة ذات أعمدة مزدوجة ، تتضمن الدراسة صب ستة عشر نموذج من البلاطات (الصفائح) الخرسانية المسلحة باستخدام خلطة خرسانية واحدة بمعدل مقاومة انضغاط(f_{cu}) مساوية إلى (28MPa) .ابعاد البلاطات متماثلة (الطول ، العرض والسمك) والمساوية إلى (470,850 و50 ملم) وبنفس الغطاء الخرساني والمساوي إلى (١٥ملم). تم فحص النماذج على فضاء بسيط الإسناد من جميع إضلاعه الأربعة وبإبعاد (420x800 ملم)، المتغيرات التي تم دراستها في هذا البحث هي شكل العمود والمسافة الصافية ما بين الأعمدة. تم تقسيم النماذج إلى مجموعتين (A) و (B) حسب شكل العمود وبواقع ثمان نماذج لكل مجموعة.أعمدة ألمجموعه (A) لها مقطع عرضي مربع الشكل طول ضلعه (٧٥ ملم) ومساحة مقطعه تساوي(٥٦٢٥ملم٢) وارتفاع العمود يساوي (٧٥ملم) والمسافة الصافية بين الأعمدة متغيرة من (٢ملم) إلى (٣٢٥ ملم) أي (0.05d)إلى (9.3d)، بينما أعمدة المجموعة (B) لها شكل دائري بقطر (٨٥ملم)ومساحة مقطعه (5675ملم٢) وارتفاع العمود يساوي (٧٥ملم) والمسافة الصافية بين الأعمدة متغيرة من (٢ملم) إلى (315 ملم) أي (0.05d)إلى (9d) .بينت نتائج الفحوصات أن حمل الفشل وصل إلى أعلى قيمة عندما أصبحت المسافة بين الأعمدة مساوية إلى (9.3d و 9d) للمجموعتين(AوB) على التوالي ، وتتناقص هذه القيمة بنسبة تتراوح بين (6.5-33%) و (16.4-35.9%) من أقصى حمل للفشل عندما تناقصت المسافة بين الأعمدة من (7d) إلى (0.05d).عندما تكون المسافة الصافية بين الاعمدة بحدود (0.05dالى 7d) بينت نتائج الفحوصات أن منطقة الفشل تنفصل عن البلاطة كجزء واحد، لكن عندما تكون المسافة الصافية ما بين الاعمدة بحدود (9.3d و 9d) للمجموعتين (A) و (B) على التوالي فأن منطقة الفشل تنفصل عن البلاطة كجزئين منفصلين .

Notation

d= Effective depth of slab;

X= Clear Distance between columns;

f_{cu}= Ultimate cube compressive strength;

f_y = Yield tensile strength;

f_u= Ultimate tensile strength;

ϕ = D m r o r o rc d b r .

Introduction

Flat plates are widely used in multi-storey structures such as office buildings and car parks. A flat slab structure is composed of slabs and columns only, interconnected .Concrete flat slab floors provide an elegant form of construction, which simplifies and speeds up site operations, allows easy and flexible partition of space and reduces the overall height of buildings[1] .

Punching shear failure is a local phenomenon which generally occurs in a brittle manner, at concentrated load or column support regions. This type of failure is catastrophic because no external, visible signs are shown prior to the occurrence of failure, Therefore; it has been of special interest to engineers to try to understand the behavior of slab column connections. However, although extensive research has been done on the punching shear strength of slabs, to date there is still no generally applicable, rational theory. The current building code design procedures are based on empirical studies and concerns have been raised about their ability to accurately predict the punching shear strength of slabs for al1 situations [2] Punching shear of flat plate which has one column were interested byseveral researches [3, 4]

In some cases of the flat plate structures, the slab has two or more columns close together. The purpose of this state is either for architectural design or structural requirements such as when the foundation has two piles close together and when combined foundation supports two columns separated by expansion joint.

The punching shear behavior of the close columns may be either as one column or separated columns, this is unknown. This study investigates the effect of separation distance of the columns on punching shear behavior.

Experimental Work

1-Experimental WORK

The test program consists of fabricating and testing sixteen reinforced concrete slabs with coupled columns using a single concrete mix with average cube compressive All slab specimens have the same dimensions strength (f_{cu}) equal to (28 MPa). (length, width and thickness) equal to (850, 470 and 50mm) and concrete cover of (15 mm); see Figures (1) and (2). The variables investigated in this study are the shape of column and the distance between columns in the slab specimen. The slab specimens are divided into two groups (A) and (B), each group includes eight slabs, Table (1). 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 (433MPa), **Figure (2)** and **Table (1)** show the details of column shapes and distance between columns.

2-Materials

The properties and description of materials used in manufacturing the test specimens are reported and presented in Table (2); and the concrete mix proportions are reported and presented in **Table (3**).

3-Test Measurements and Instrumentation

Hydraulic universal testing machine (MFL system) was 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 were placed underneath the bottom face of each span at mid.

4- Mixing, Casting, Compacting and Curing Procedure

The mixing procedure was as follows:-

1- Before mixing, all quantities are weighed and packed in clean containers.

2- 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.

3- The cement is then added to the mixer, and water is added gradually to the mix. The total mixing time is (8-10 minutes).

4- The moulds are coated with oil before putting the reinforcing bar, or casting the control specimens.

5-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.

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.

Results and Discussions

1 -General

In this study, (16) slab specimens are tested. These slabs are identical in size and ratio of steel reinforcement, but different in shape of column and the clear distance between columns in the slab specimen. According to these variables, ultimate loads, crack patterns as well as shapes of failure are different from each other, and these slabs are divided according to column shape into two groups, (A) and (B).

2- Crack Pattern

The test results of cracking and ultimate loads are reported and presented in Table (4). When load is applied to these slab specimens, the first crack is formed at about (14.8-21.9%) and (12.2- 19%) of the ultimate load for each slab for group (A) and (B) respectively.

. 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. **Figures (3 and 4)** illustrate crack patterns and failure modes of group (A) and (B)

Also, it is observed that, the flexural cracks do not appear in the tensile face of these slabs. This may be due to the effect of the high effective depth and the steel reinforcement in improving ductility, flexural strength and punching shear resistance of concrete slabs. This may be attributed to the fact that, for high reinforcement ratios, a brittle punching failure can occur, and yield lines can form, but these do not necessarily occur(park and gamble,1980)

From **Figures (3 and 4)** it is evident that the capillary cracks appear in the tensile face of the slabs when the moment..

3- Load – Deflection Behavior

The deflection results of groups (A) and (B) are illustrated **in Table (5)**. The test results show that , for group(A) ,the maximum deflection at ultimate load occurs when the clear distance between columns is equal to (1.5d)(slab AS4), and the deflection at the ultimate load decreases when the distance between columns is decreased or increased**. Figure (5)** show the load-deflection relationship of the slabs in this group.

Also, it is observed that, for group (B) the maximum deflection at ultimate load is in the range of (7.6 to 8.5mm) for slabs (BC2, BC3, BC4, BC5, BC6 and BC7) and about (6.5 and 7.03mm) for slabs (BC1 and BC8) respectively. **Figure (6)** show the load-deflection relationship of the slabs in this group.

4 -Ultimate Loads

Ultimate load capacity for punching failure is illustrated in **Table (5).**The test results show that:-

1- The ultimate load of the maximum value occurs when the distance between columns is equal to (9.3d and 9d) for groups (A) and (B) respectively.

2-The maximum ultimate load is reached when separation of failure zone occurs.

3-The ultimate load of group (A) decreases by about (6.5 to 33.9) % of the maximum ultimate load when the clear distance between columns varies between (7d 0.05d) as shown in **Figure (7- a).**

4-The ultimate load of group (B) decreases by about (16.4 to 35.9) % of the maximum ultimate load when the clear distance between columns varies between (7d to 0.05d) as shown in **Figure (6- b)**.**Figure (7- a)** show that the curve can be divided into two parts, the first part is between distance (0.05d)and (1.5d) and second part is between distance (1.5d) and (9.3d) . All points in the first part lay on the same line and those points in second part have the same tangent; the slope of the first part is greater than that of the second part.

5 -Failure Angles

The failure angles of the punching pyramid are measured by indicating the dimensions of crushed zone around the center line passing through the loaded area. From **Table (6)**, it is noticed that the angles of failure zone for short direction for all slabs are in the range of (20° -23°). while, theangle of failure zone for long direction in increases from 14° to 22° when the clear distance between columns varies from (0.05d) to (9.3d) ,and incontrest for group (B), it decreases from 21° to 15° when the clear distance between columns varies from (0.05d) to (9d) . The angles in long and short direction are approximately identical in slabs (AS8 and BC8) at which separation occurs.

6 -Area of the Failure Zone

The areas and perimeters of the punching failure zones are measured and their values are illustrated in **Table (7)**. When the distance between columns is equal to (7d), slabs (AS7) and (BC7), the size of failure zone recorded the maximum value. The failure zone separates into two zones under columns when the clear distance between columns equal to (9.3d and 9d) for group (A) and (B) respectively, i. e at slabs (AS8) and (BC8).

7- Comparative Notes between Group (A) and Group (B)

The ultimate loads for slabs in group (B) are greater than those of slab in group (A) (with the same clear distance between columns) ,as shown in **Figure (8)**, although the areas of circular and square columns are identical . This difference in the ultimate load values happens because the side length of circular columns is greater than that for the square columns and (columns with sharp edges resist less load compared to columns with round edges)[6] . The ultimate load varies in the ranges (41-62 kN) for group (A) and (52.5-82 kN) for group (B).

The difference between the maximum ultimate load and the minimum ultimate load for group (A) (62- 41kN) is smaller than that for group (B) (82-52.5 kN), because the length of the adjacent of the columns in group (A) is greater than that in group (B), see **Figure (8)**

The failure angles in short direction are approximately identical for both groups (A) and (B); but in long direction, these angles begin to increase with the increase in clear distance between columns for group (A) and begin to decrease with the increase in clear distance for group (B), because columns in group (A) have sharp edges while columns in group (B) have rounded edges. The angles in long direction are in general greater than those in group (A).Therefore, the size of failure zone in group (B) is larger than the size of failure zone in group (A), as shown in **Figure (9).**

Conclusions

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

1- The ultimate loads for slabs which have circular columns are greater than those of slabs which have square columns (for the same clear distance between columns), and the cross sectional areas of both, circular and square columns, are identical.

2- The ultimate load has the distance maximum values the distance between columns, is equal to (9.3d and 9d). for slab have square and circular columns respectively.

3- The maximum ultimate load is reached when separation of failure zone occurs.

4- The ultimate load of slabs which have square columns decreases by about (6.5 to 33.9) % of the maximum ultimate load when the clear distance between columns decreases from (7d 0.05d).

5- The ultimate load of slabs which have circular columns decreases by about (16.4 to 35.9) % of the maximum ultimate load when the clear distance between columns varies between (7d to 0.05d).

6- The angles of failure zone for short direction for all slabs are in the range of (20° -23°).

7- The angle of failure zone for long direction increases from 14° to 22° when the clear distance between columns varies between (0.05d to 9.3d) for slabs which have square columns ,while this angle decreases from 21° to 15° when the clear distance between columns varies between (0.05d to 9d) for slabs which have circular columns .

8- The angles in long and short direction are approximately identical in slabs (AS8 and BC8) at which separation occurs.

9- When the distance between columns is equal to (7d), the size of failure zone records the maximum value.

10- The failure zone separates into two zones under columns when the clear distance between columns is equal to (9.3d and 9d) for slabs have square and circular column respectively.

References

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[6] BS 8110, **"*Code of Practice for Design and Construction*"**, British Standard Institution,

1997

Table (1): Dimension Details of Slabs Tes

Group	Slab Designation	shape of column	Column size (mm)	Area of column $(mm)^2$	Clear Distance between columns	
					X (mm)	X/d
A	AS1*	Square	75× 75	5625	2	0.05d
	AS2				18	0.5d
	AS3				35	D
	AS4				53	1.5d
	AS5				105	3d
	AS6				175	5d
	AS7				245	7d
	AS8				325	9.28d
B	BC1*	Circular	85	5674	2	0.05d
	BC2				18	0.5d
	BC3				35	D
	BC4				53	1.5d
	BC5				105	3d
	BC6				175	5d
	BC7				245	7d
	BC8				315	9d

*S, C: Square and Circular column cross-section respectively

Table (2) Description of Construction Materials

Material	Descriptions
Cement	Ordinary Portland Cement (Type I)
Sand	Natural sand from Al-Ukhaider region with maximum size of (4.75mm).
Gravel	Crushed gravel with maximum size of (10mm) from Al-Nibaee area.
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 (433MPa) and the average ultimate strength (f_u) is (471MPa).
Water	Tap water.

Table (3): 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

Table (4): First Crack and Ultimate Loads of Slabs

Group	Slab	Clear distance between columns		f_{cu} (MPa)	First crack load (P_{cr}) (kN)	Ultimate Load (P_u) (kN)	$\frac{Pcr}{Pu}$ (%)
		(X) mm	X/d				
A	AS1	2	0.05	26.90	9	41	21.9
	AS2	18	0.5	26.63	7	44	15.9
	AS3	35	1	26.63	7	47	14.8
	AS4	53	1.5	28.40	10	50.5	19.8
	AS5	105	3	28.40	10	53	18.8
	AS6	175	5	28.40	10	55	18.1
	AS7	245	7	28.40	10	58	17.2
	AS8	325	9.3	26.63	10.5	62	16.9
B	BC1	2	0.05	28.00	10	52.5	19.0
	BC2	18	0.5	28.00	9	57	15.7
	BC3	35	1	28.00	10	58	17.2
	BC4	53	1.5	28.00	9	58.5	15.3
	BC5	105	3	28.91	9.5	60	15.8
	BC6	175	5	28.91	10	63	15.8
	BC7	245	7	28.91	10	68.5	14.6
	BC8	315	9	28.91	10	82	12.2

Table (5) Load and Deflection Characteristics at First Crack and Ultimate Loads

Group	Slab	Deflection at first crack (mm)			Deflection at ultimate load (mm)		
		Under left column	Under Slab center	Under right column	Under left column	Under Slab center	Under right column
A	AS1	0.90	-	0.94	6.19	-	5.90
	AS2	0.95	-	0.85	6.65	-	5.90
	AS3	0.65	-	0.95	5.09	-	6.30
	AS4	1.10	-	1.50	6.10	-	7.40
	AS5	1.34	1.26	1.24	7.35	6.81	6.64
	AS6	0.85	0.96	1.14	5.58	6.15	6.85
	AS7	1.37	1.27	1.19	7.44	7.19	7.30
	AS8	0.80	1.01	1.08	5.21	5.83	6.14
B	BC1	0.91	-	1.15	5.70	-	6.50
	BC2	0.82	-	0.63	7.04	-	6.43
	BC3	0.71	-	0.97	8.10	-	7.49

	BC4	1.30	-	1.11	8.26	-	7.44
	BC5	1.45	1.44	1.44	7.60	7.45	7.45
	BC6	0.68	0.74	0.82	7.89	7.80	8.50
	BC7	0.77	0.62	0.54	8.05	7.93	6.79

Group A				Group B			
Slab	**Failure Angle in long direction**		**Failure Angle in short direction**	**Slab**	**Failure Angle in long direction**		**Failure Angle in short direction**
AS1	14		23	BC1	21		23
AS2	15		21	BC2	19		20
AS3	15		21	BC3	17		22
AS4	18		23	BC4	17		22
AS5	18		23	BC5	16		21
AS6	22		21	BC6	15		20
AS7	22		22	BC7	15		20
AS8	Right col.	21	23	BC8	Right col.	21	23
	left col.	22	22		Left col.	23	23

Table (6) Failure Angle for tested slabs

Table (7): Area and Perimeter of the Failure Zone

Group A			Group B		
Slab	**Measured area (mm^2)**	**Measured perimeter (mm)**	**Slab**	**Measured area (mm^2)**	**Measured perimeter (mm)**
AS1	169715	1579	BC1	130889	1596
AS2	170379	1807	BC2	185876	2047
AS3	178235	1826	BC3	195294	1911
AS4	146069	1903	BC4	199163	2131
AS5	173081	2235	BC5	237136	2316
AS6	190079	2595	BC6	249495	2391
AS7	225257	2220	BC7	255220	2412
AS8	114381	1590	BC8	105494	1484
	101747	1535		89525	1283

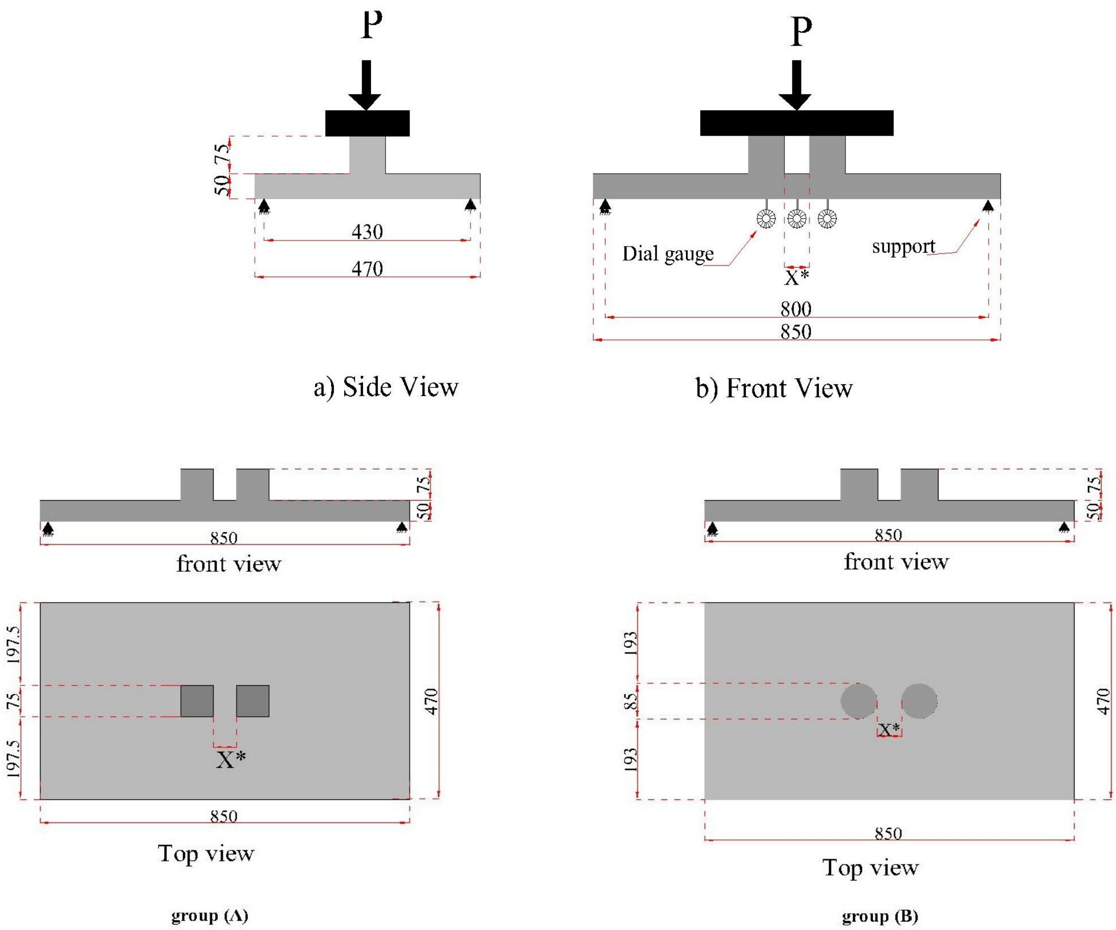


Figure (1) Details of Slab Specimens and Load Arrangement

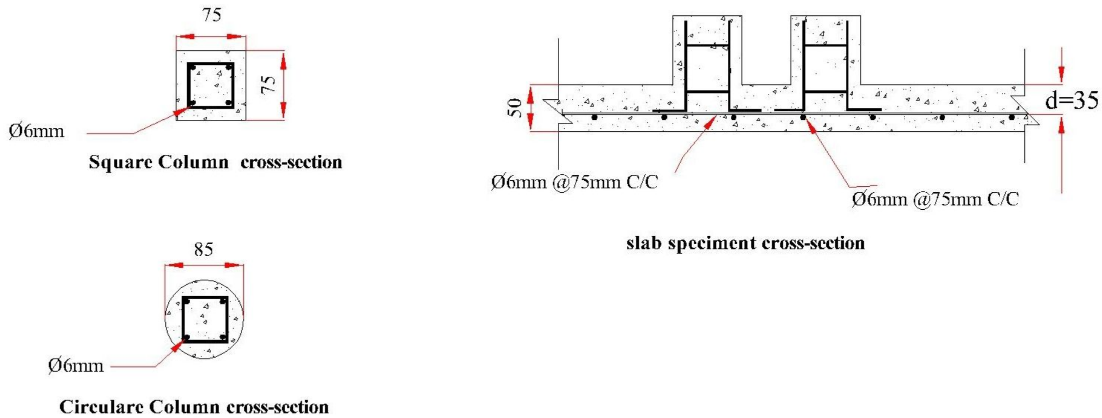


Figure (2) Details of Specimens Cross Section

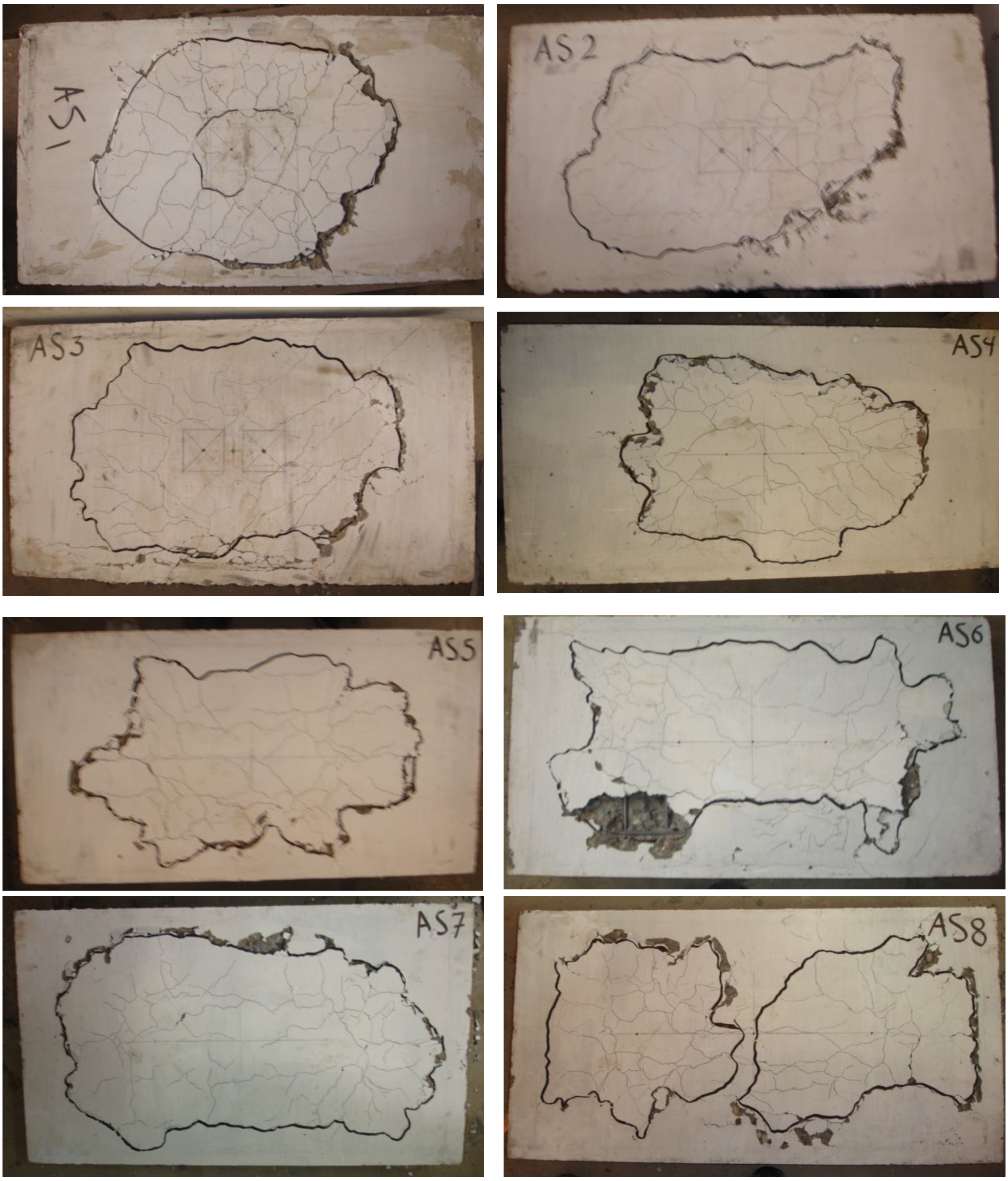


Figure (3) Crack Patterns of Group (A) at bottom Face

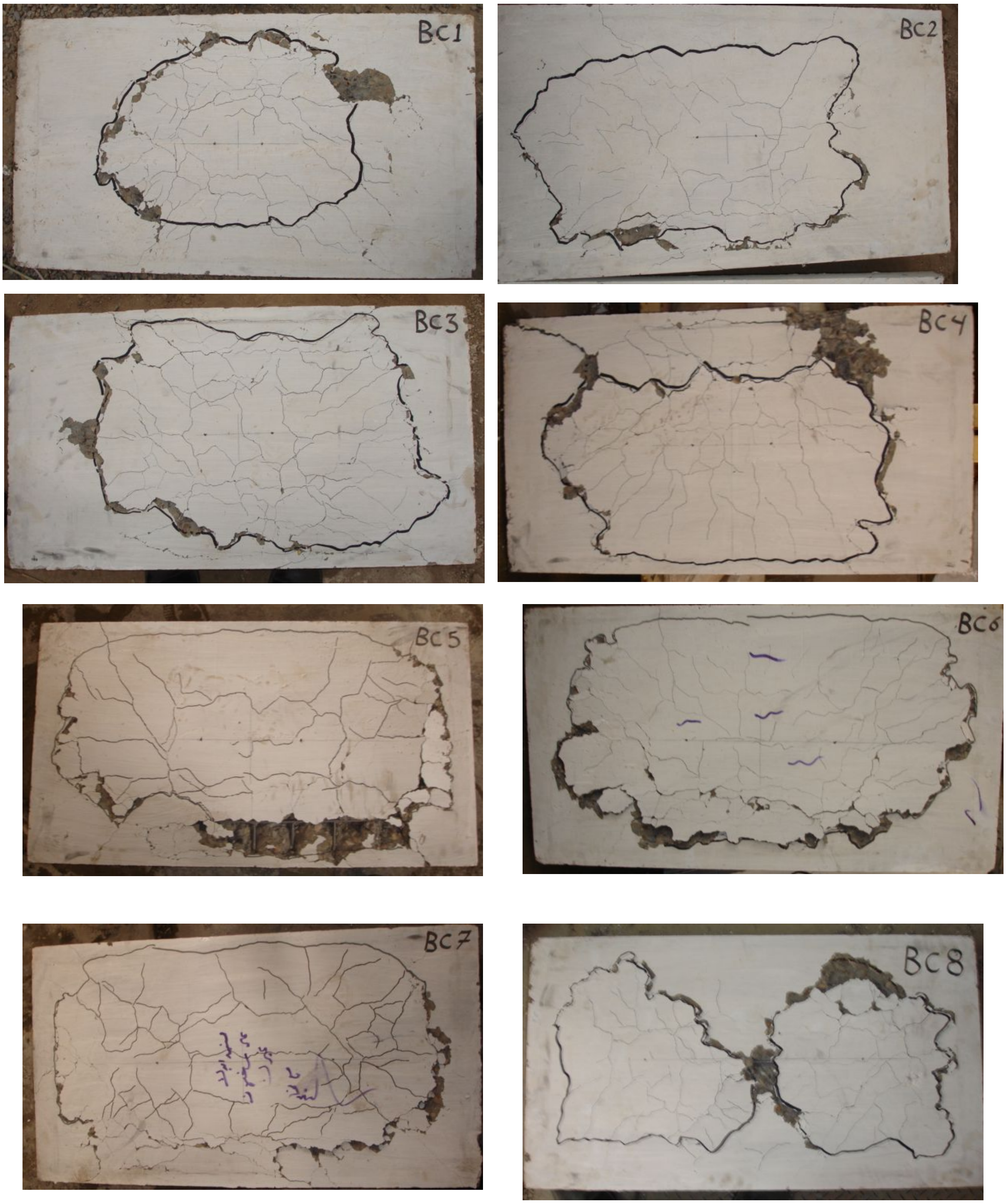
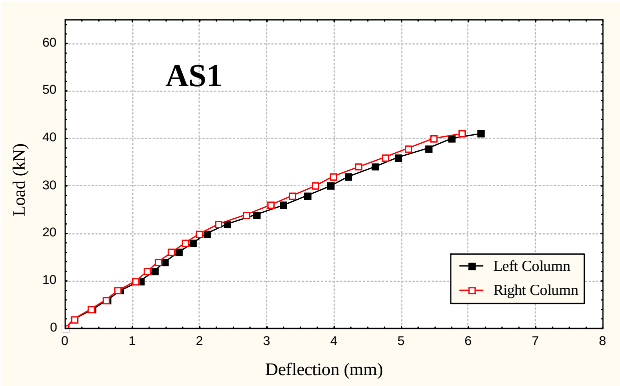
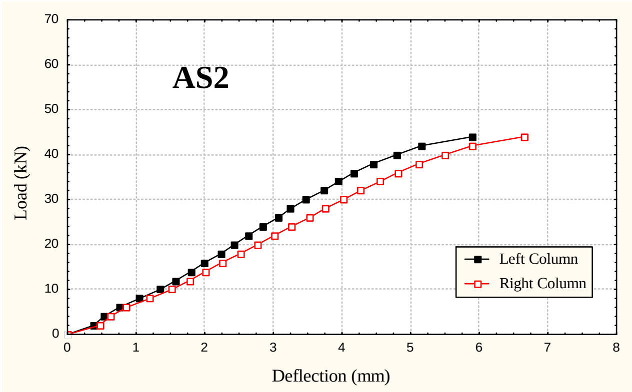
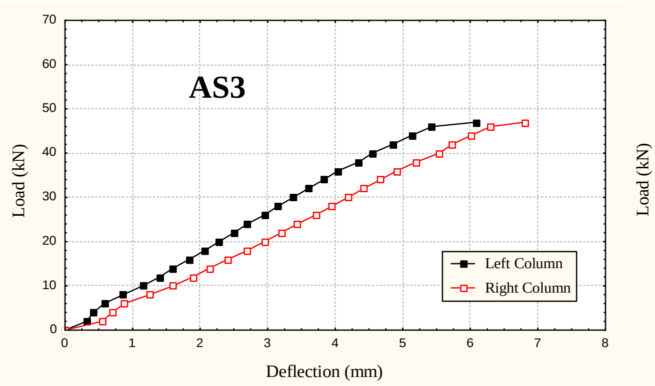
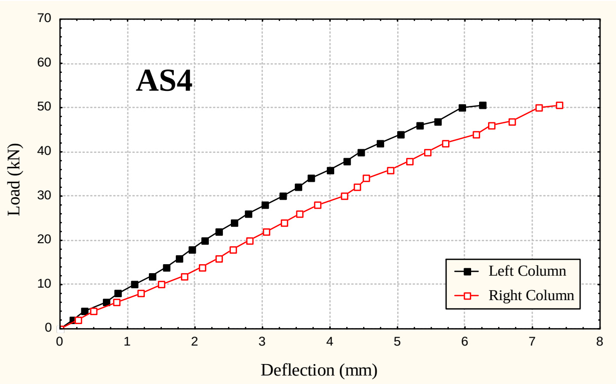


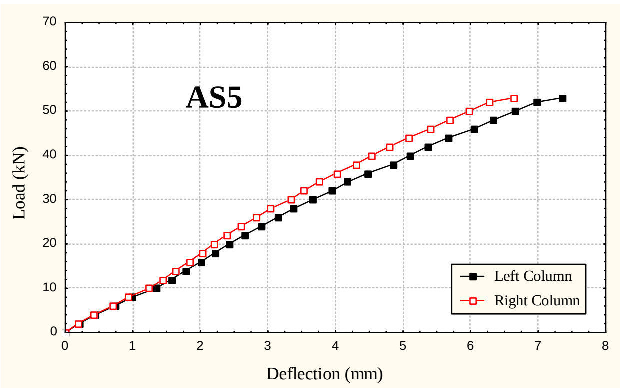
Figure (4) Crack Patterns of Group (B) at bottom Face

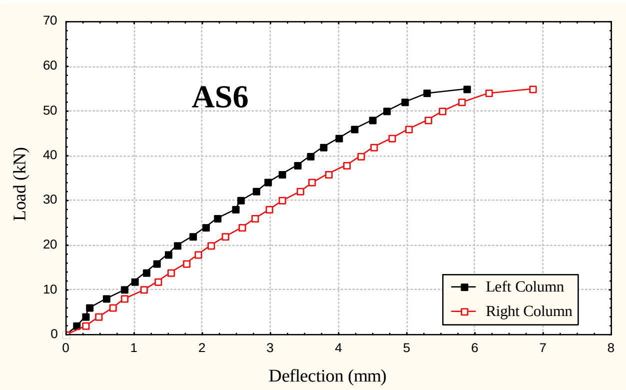

AS1
Load (kN)
Deflection (mm)
Left Column
Right Column

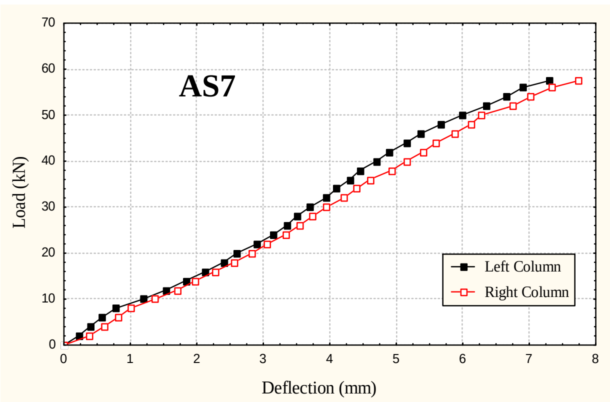

AS2
Load (kN)
Deflection (mm)
Left Column
Right Column

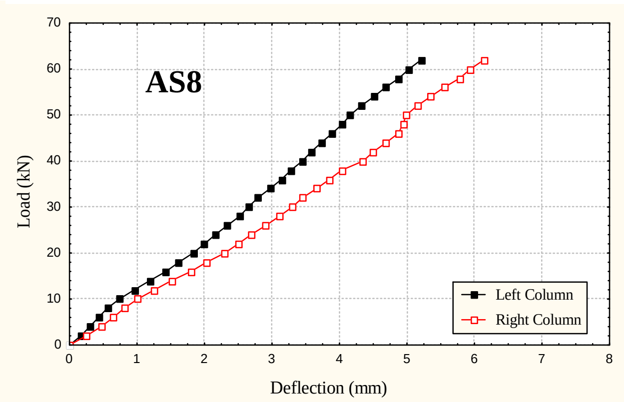

AS3
Load (kN)
Deflection (mm)
Left Column
Right Column


AS4
Load (kN)
Deflection (mm)
Left Column
Right Column


AS5
Load (kN)
Deflection (mm)
Left Column
Right Column


AS6
Load (kN)
Deflection (mm)
Left Column
Right Column


AS7
Load (kN)
Deflection (mm)
Left Column
Right Column


AS8
Load (kN)
Deflection (mm)
Left Column
Right Column

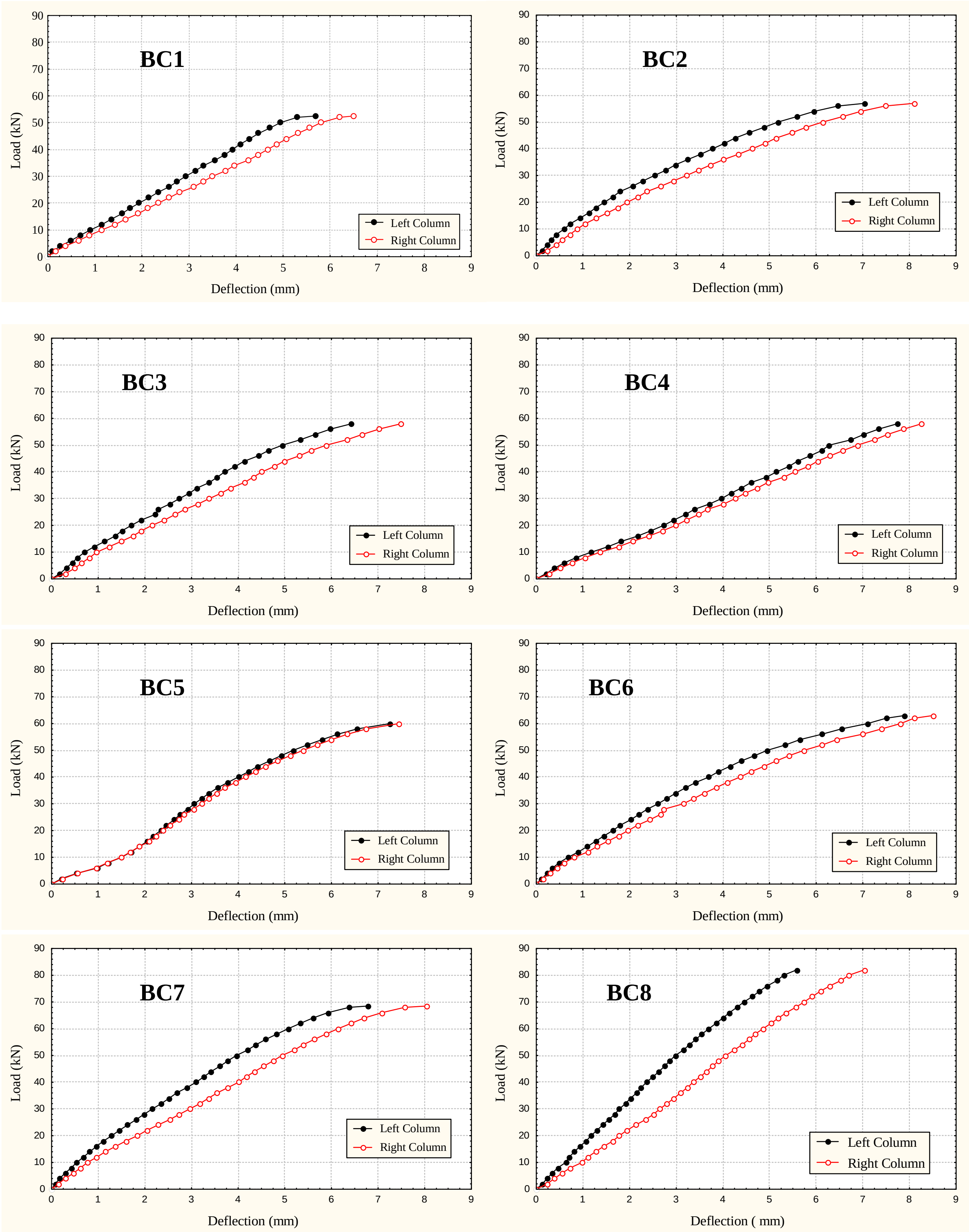
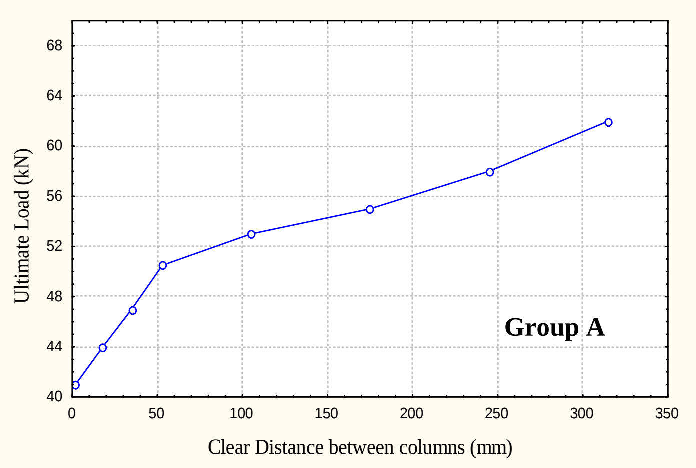
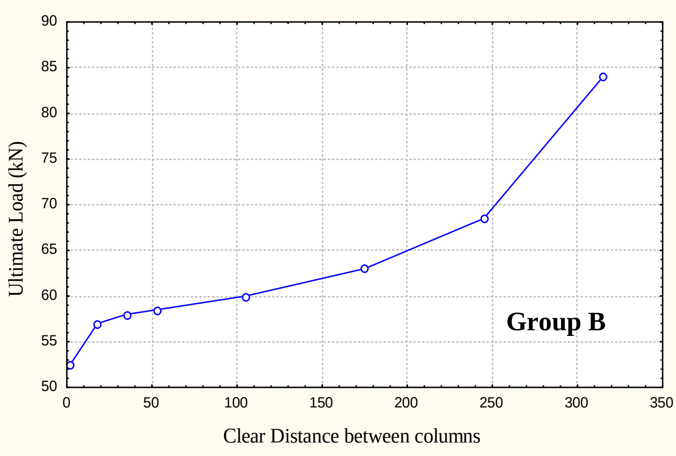


Figure (5) Load –Deflection Curve for Group A





(a) **(b)**

Figure (7) Load - Clear Distance between Columns

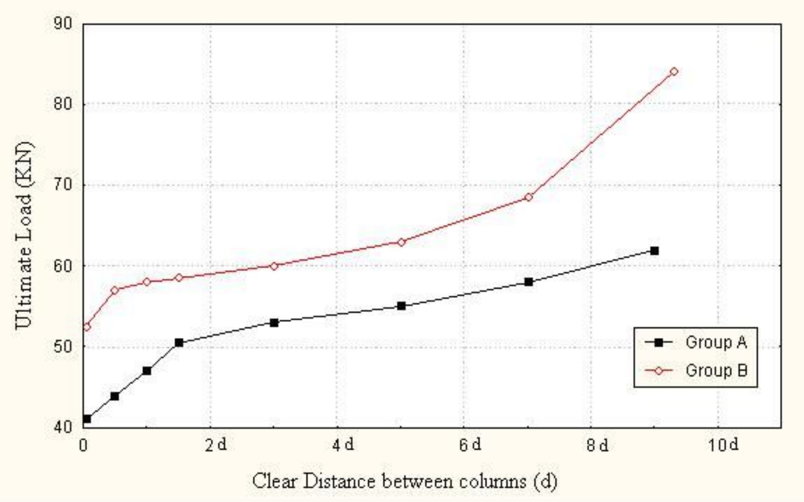


Figure (8) Load-Clear Distance between Columns Relationship

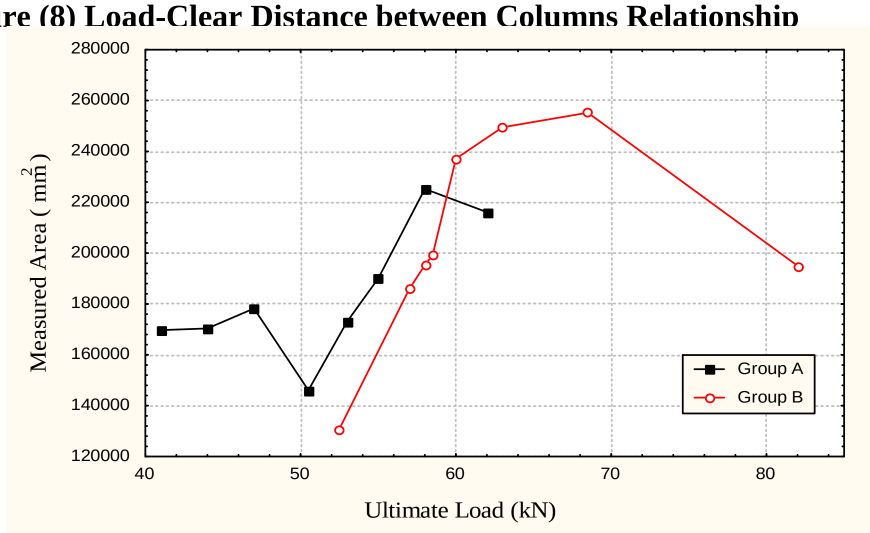


Figure (9) Measured Area –Load Relationship