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Punching Strength of Reactive Powder Reinforced Concrete Flat Slabs

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A B S T R A C T

This research is devoted to investigating experimentally the punching shear strength of reactive powder concrete slabs under monotonic loading. All slabs have the same flexural reinforcement and same dimensions (1000mm length,600mm width,50mm thickness). The experimental program includes casting and testing of sixteen slabs tested under monotonic loading. The major parameters adopted in the current research include the shape of column (circle, square), column size (two-column sizes), number of columns (one, two), and the distance between two columns (3d,5d,7d). Results showed that, the slabs with circular column sections have slightly higher ultimate load than those with square column sections. An increasing column area increases the load of punching shear failure. It was found that the ultimate failure load for slabs with two columns is greater than the slabs with one column. Related to the effect of distance between the two columns for monotonic, it was found that the slabs maximum load reaches the maximum value at distance between the two columns equal to(7d) for a circular section with a diameter of 85mm and 113mm and square section with dimensions of (100*100)mm. While the maximum failure load reaches the maximum value when the distance between two columns (d) for a square section with the dimension of (75*75)mm. Related to the crack patterns, it was noticed that for slabs with larger columns sections with the distance between columns equal to 7d, the failure zone extended (in a large direction) to the slab sides.

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مقاومة القص للبلاطات الخرسانية المسطحة ذات المسحوق التفاعلي

مصطفى المشايخي / جامعة سونبورن للتكنولوجيا، استراليا، بلال الصباري / قسم الهندسة المدنية، كلية ميامي في جامعة هينان، الصين،مازن برهان الدين عبد الرحمن و آيات احمد حسين/ قسم الهندسة المدنية، جامعة تكريت، العراق.

الخلاصة

كرس هذا البحث لاستقصاء السلوك العملي لمقاومة القص الثاقب للسقوف الخرسانية ذات المسحوق التفاعلي تحت تأثير التحميل الاحادي الاتجاه. جميع الالواح لها نفس تقوية الانحناء ونفس الابعاد (طول 1000, عرض 600, سمك 50) ملم. يتضمن البرنامج العملي صب وفحص ستة عشر لوحا تضمن المتغيرات الرئيسية المعتمدة في البحث الحالي شكل العمود (دائري, مربع), حجم العمود(حجمين للعمود), عدد الاعمدة (واحد, اثنان) والمسافة بين العمودين (d,4d,7d). اظهرت النتائج ان الالواح ذات المقطع العرضي الدائري لها حمل اقصى اعلى قليلا من تلك التي لها مقطع عرضي مربع. كما ان زيادة المساحة يعني زيادة محيط منطقة الفشل وبالتالي تقليل الاجهادات التي تنتقل من العمود الى البلاطة. لقد وجد ان حمل الفشل النهائي للبلاطات التي تحتوي على عمودين اكبر من تلك الموجودة في الالواح التي تحتوي على عمود واحد. فيما يتعلق بتأثير المسافة بين العمودين للتحميل الرتيب . كما وجد ان حمل الفشل النهائي يصل الى القيمة القصوى عندما تكون المسافة بين العمودين (7d) للمقطع الدائري ذات قطر 85 ملم و113 ملم والمقطع المربع بأبعاد (100*100)ملم. بينما يصل حمل الفشل النهائي الى الحد الاقصى للقيمة عند المسافة بين عمودين (d) للمقطع المربع بأبعاد (75*75)ملم. فيما يتعلق بأنماط الشقوق لوحظ انه بالنسبة للبلاطات ذات العمودين والمسافة بينهم (7d)فان منطقة الفشل تمتد في الاتجاه الكبير الى جوانب البلاطة.

1. INTRODUCTION

Reinforced concrete floor construction that not requiring beams and girders to transmit the floor load to supporting columns is called "flat slab". The benefits of choosing flat slabs include the speed of construction, minimum depth solution, flexibility in the plan layout, a flat soffit (clean finishes and freedom of layout of services), and scope and space for the use of flying forms and lower construction cost. Much other compensation can be obtained using this type of construction, such as a reduction of loads applying on the columns and foundations[1]. One of the main disadvantages of using this type of slab is the opportunity of a punching shear failure for a low load level. The rupture by punching takes place suddenly, with a little caution, approximately without ductility, which may lead to a progressive collapse (spread of a failure that was originally held in a small part of the structure, in which the resulting damage is disproportionately larger than the original)[2]. Reactive Powder Concrete (RPC) is one of the most important and latest progress in concrete technology. Many studies clarify the efficiency and effectiveness of using RPC in structural elements [3],[4],[5],[6]. It is also classified as a form of Ultra-High-Performance Concrete (UHPC) which is distinguished by a dense combination of high cement content, advanced mechanical properties, excellent environmental resistance, and in main cases including a steel fiber to decrease concrete brittleness.

Abdul and Samir,2017 [7] studied the punching shear strength of reactive powder concrete slabs. The experimental program included investigating the effective thickness of the slab on the first crack, type of failure, load-deflection curve, and comparison of the ultimate punching shear capacity with the ACI-440 equation. All tested slabs were with dimensions of (1150×1150)mm with variable thickness (80,100,120,150)mm. Experimental tests showed that ultimate punching shear capacity was increased approximately 70% by increasing the thickness of the RPC slab by 55%.

Kiss and Hassan,2013[8] studied the behavior of RPC and modified reactive powder concrete MRPC slabs subjected to punching shear. The research program included studying the effect of an absence of coarse aggregates as well as the steel volumetric ratio (V_f) on mechanical properties of RPC and MRPC like uniaxial stress-strain relationship in compression, compressive strength, splitting tensile strength, and modulus of rupture and slab thickness on the behavior of reinforced RPC slab with dimensions of (1000×1000)mm with 50mm or 70mm thickness under static point load. Experimental results showed that the inclusion of steel fibers in all RPC and MRPC slabs resulted in a significantly enhanced ductility which made the slabs fail gradually in a ductile manner, and enhanced stiffness, reduced crack width, reduced rate of crack propagation, and preserving the whole section.

Halas and Shatha2018[9] studied the response of reinforced RPC slabs under monotype and repeated loading types. Six simply supported two-way slabs of (1000×1000×70)mm. All the tested slabs have the same reinforcement details and material properties with different steel fibers content. The specimens are divided into three groups, each one had a different steel fiber volumetric percentage (0.5,1,1.5)%. In each group, one specimen was tested under static load and the other under repeated loading. The results of the monotype test showed that increasing steel fibers percentage from 0.5% to 1% and from 1% to 1.5%, lead to an increase in the ultimate load by (36.1%, 17.0%) and increase the maximum deflection by (33.6% and 34.0%), respectively.

2. WORK SIGNIFICANCE AND AIM

The flat slab structural element is used in constructions, however, this type of slab is subjected to punching shear failure with a lower loading value. Previous studies have not studied the effect of shape, size of the column, and the clear distance between the two-column on the punching shear strength and behavior of slabs under monotonic load. This research aims to investigate the punching shear strength and behavior of RPC slabs that have columns with different properties under static concentrated load.

3. EXPERIMENTAL STUDY

3.1 Materials

The reactive powder concrete (RPC)mixes used in this study require a high-quality material. Table 1 presented in brief the description of the used materials. Deformed reinforcing steel bars are used in this work with a nominal diameter of 6mm.

3.2 Experimental program

The experimental program includes casting and testing of sixteen Reactive Powder reinforced concrete slabs that were tested under monotonic load. All slabs have the same dimensions of (1000*600*50)mm and the same reinforcements. All slab specimens are simply supported along all edges which are subjected to concentrated loading load applied at the center of gravity of each slab. The applied load is transformed from the testing machine through a center column with different shapes and sizes. Table2 shows the general details and variables of the tested slabs. The effects of four main parameters have been investigated throughout this study :

1. Shape of column(square and circle).
2. Column size,(two sizes for each section shape).
3. Number of columns; (one and two).
4. The distance between two-column,(d,4dand 7d).

3.3 Slabs Details

The test program consists of producing and testing sixteen RPC reinforced two-way slabs with single columns and coupled columns using the same concrete mix. All slab specimens have the same dimensions (length, width, and thickness) equal to (1000×600×50)mm and a concrete cover of 10mm. Deformed 6 mm diameter with 70mm c/c spacing each way is used as a flexural reinforcement in tension faces with square and circular columns sections. Two section shapes of the columns are used (square and circle), with two areas for each column section. The details of the slabs are stated in Table 2. All square columns were reinforced with 4ø 6mm bars and all circular columns were reinforced with 6ø 6mm bars. Figs. 1, 2 show the details of the reinforced RPC slabs that were tested in this study.

3.4 Concrete Mix Design

To produce the RPC, the material mix proportions stated in Table 3 are used in this work. However, several trial mixes have been made through the earlier stage of the present study to produce RPC and appropriate workability (flow table of 105±5%) ASTM C 109/C 109M-99 [10]. The workability for all types of RPC mixes is tested using the flow table test, The flow table spread value was 105 ±5% for all mixes. The volume percentage of steel fibers were used in this mix is (V_f = 1%).

Table1

Description of Material

Material	Description
Cement	Ordinary Portland cement (Type I) Satisfied to the Iraqi specification No.5/ 1984 [11]
Siliceous Sand	Siliceous sand (sieved over 0.6mm sieve)conforms to the B.S. specification No.882/ 1992[12]
Micro silica fume	It is an ultra-fine gray powder commercially named (Mega Add MS(D)) conforms to the ASTM C 1240-03[13]
Super Plasticizer	The admixture Sika®Viscocrete 5930- L, conforms to ASTM-C 494 Types G and F[14]
Steel fibers	Straight steel fibers, gold-colored, ultimate tensile strength up to 2600 MPa and a diameter 0.2mm and length 12mm
Water	Clean tap water (used for mixing and curing).

Table 2

General Details and Variable of the Tested Slabs

Slab Designation	No of columns	Shape of column	Column size(mm)
MCS_1	One	Circular	85
MSS_1	One	Square	(75*75)
MCL_1	One	Circular	113
MSL_1	One	Square	(100*100)
MCS_{2-d}	Two	Circular	85
MCS_{2-4d}	Two	Circular	85
MCS_{2-7d}	Two	Circular	85
MSS_{2-d}	Two	Square	(75*75)
MSS_{2-4d}	Two	Square	(75*75)
MSS_{2-7d}	Two	Square	(75*75)
MCL_{2-d}	Two	Circular	113
MCL_{2-4d}	Two	Circular	113
MCL_{2-7d}	Two	Circular	113
MSL_{2-d}	Two	Square	(100*100)
MSL_{2-4d}	Two	Square	(100*100)
MSL_{2-7d}	Two	Square	(100*100)

Table 3

Mix proportions

Constituent	Fine sand (600μm)	Cement	Micro silica	Water	SP	Steel Fiber
Amount(kg/m^3)	1070	963	107	214	32	78

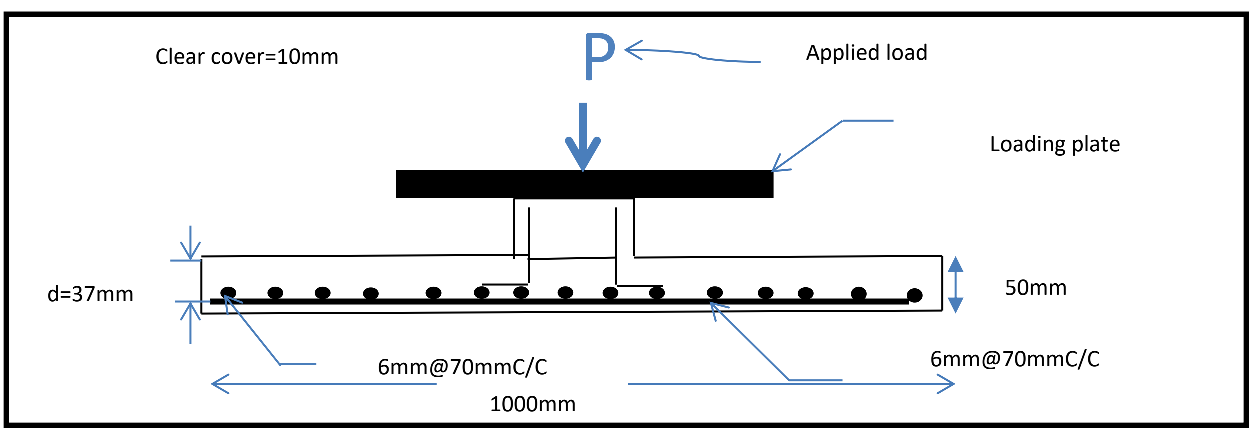

Fig.1. Details of specimens Cross-section and Load Arrangement to one column

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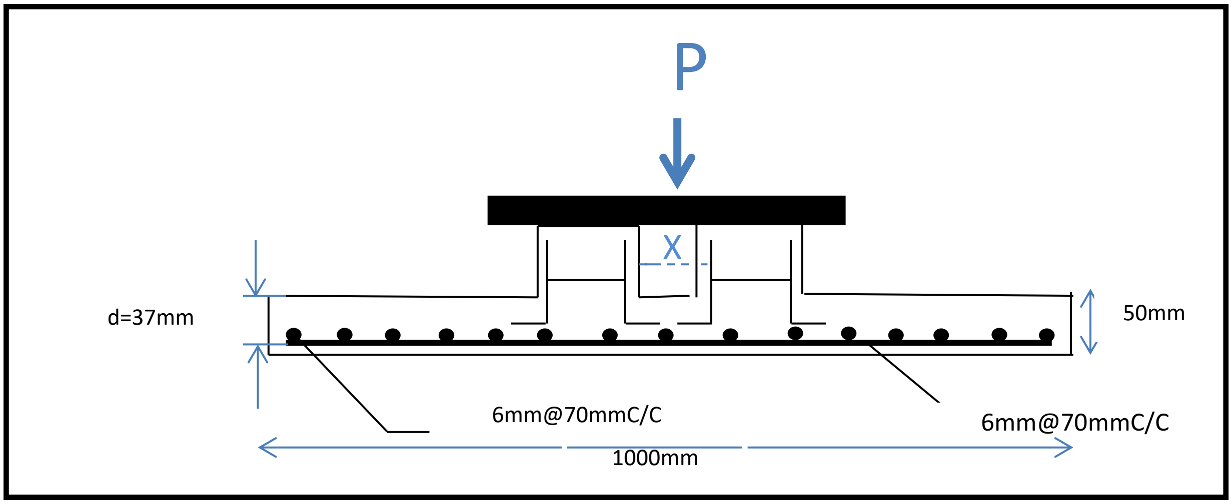

Fig.2. Details of specimens Cross-section and Load Arrangement to two columns.

3.5 *Concrete Mixing Procedure*

Steel molds are used for casting slabs, mixing procedure is important to gain the required workability, see plate 1 and plate 2. The mixer of capacity (0.05) m^3 is used to cast the concrete. A mixing procedure proposed by ASTM C293-02 [15] is implemented throughout this study to produce RPC in a simple way, which include:

1. Mixing of sand and micro silica fume first for 3minutes.

2. Adding the cement and mix for another 3minutes.

3. Superplasticizer is mixed with the water, then the liquid is added to the mix and the mixing process goes on for 4 minutes.

4. At the final, steel fibers are added in small quantities while the mixer is rotating for 3 minutes, plate1 shows the process of casting the slabs.

The specimens are cured (by water) until the 28 day age of concrete.

3.6 *Test Setup*

the slab specimens are cleaned and painted white to distinguish the crack propagation. Also, the loading point and the dial gauge location were marked on slabs. The slabs, with dimension(1000×600×50)mm, are sited on the testing machine, as shown in plates 2 with steel plate of dimensions 500mm×100mm×10mm (length ×width ×depth)have been set over the load points to avoid stress concentrations on the upper face of the slabs during loading, all slabs have been loaded to failure. Failure happen, when the slab failed suddenly at simultaneity with the load indicator stopped record load values and the deflection increased very rapidly. The ultimate load is recorded, and the load is removed and the crack pattern and the mode of failure was determined.

Plate .1 Casting of slabs

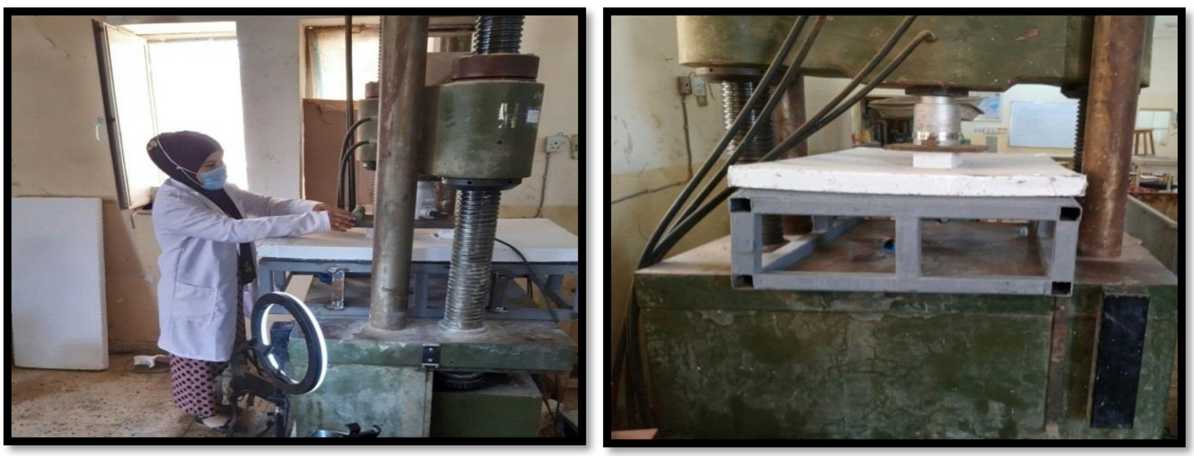

Plate.2 Slabs under testing

3.7 *Mechanical Properties of RPC Mixes*

The control specimens were mixed and cast to determine the compressive as well as the tensile strength of the concrete. Three cubes (70×70×70)mm were examined by BS1881-116[16], three prisms (40mm×40mm×140mm) were tested according to ASTM C293-02[17] to determine the compression strength and modulus of rupture respectively. The results were 94.5 MPa and 34 MPa respectively for the average of three specimens results.

4. RESULTS AND DISCUSSION

Test results include the cracking load, ultimate load, and its corresponding deflections, load-deflection relationship. The test results are presented in Table 6.

4.1 *Ultimate Load P_u*

4.1.1 *Effect of column shape*

From Fig.1, it can be noted that the slabs with circular column sections have a slightly higher ultimate load than those with square column sections. The increases were (1.6%and 8.4%) for columns of smaller and larger columns area respectively. This difference in the ultimate load values happens because of stress concentration at square column corners so failure occurs faster.

4.1.2 *Effect of column size*

Form Fig.1, this can be attributed to that the increase of column area will be increasing the column perimeter, and consequently, decrease the concentration of stresses transmitted from column to slab. The increase was (20.91% and 20.37%)for columns of circular and square sections respectively.

4.1.3 *Effect of columns number*

The number of column transient the load to the reinforced concrete slabs affect the punching shear capacity of the slabs. This study investigates the effect of the separation distance of the columns and one column on punching shear behavior tested under monotonic loading. Where, Figures.1,2,3,4,5showed that the ultimate loads for slabs that have two columns are greater than those of slabs that have one column because the increasing of column area will be increasing the column perimeter, and consequently, decrease the concentration of stresses transmitted from column to slab.

4.1.4 *Effect of the distance between two column*

A- *Effect the distance between two columns for the MCS_2 slab*

Generally, It can be observed from Fig.2 that the ultimate failure load of slabs increase with increasing the distance between two columns the distance equal to 7d, for different columns size and shape the maximum failure load was for a slab of circular column shape with size equal to 85mm for the distance between columns equal to 7d. The area of the failure zone increase when the distance between columns increases.

B-*Effect the distance between two columns for MSS2 slab*

Generally, It can be noticed from Fig.3 that the ultimate failure load of slabs increase with the distance between two columns equal to d, for different columns size and shape the maximum failure load was for a slab of square column shape with size equal to (75*75)mm for the distance between two columns equal to d. The failure zone area increase when the distance between columns increases.

C-*Effect the distance between two columns forMCL_2*

Generally, It can be observed from Fig.4 that the ultimate failure load of slabs increases with increasing the distance between two columns for different columns size and shapes. The maximum failure load was for a slab of circular column shape with a size equal to 113mm for the distance between columns equal to 7d. The area of the failure zone increase when the distance between columns increases. The area of the cracking zone increase when the distance between columns increases at the sides of the columns on the slab tension face and other cracks from at the slab central region, except for slab ($MSL_{2\text{-}7d}$) where cracks extend to the end of the slab. plate 3 and plate 4 showed a crack pattern for slabs one column and two columns after testing respectively.

D- *Effect the distance between two columns for MSL_2*

Generally, it can be noticed from Fig.5 that the ultimate failure load of slabs increase with increasing the distance between two columns the distance equal to 7d, for different columns size and shape the maximum failure load was for a slab of square column shape with size equal to (100*100)mm for the distance between columns equal to 7d. The area of the failure zone increase when the distance between columns increases.

5. CRACK PATTERN FOR SLABS

All the tested Sixteen reinforced Reactive Powder Concrete slabs failed in shear. For the monotonic loading type, the slabs are tested by applying an increasing load up to failure. Few flexural cracks were appear in the slabs tensile face, the increasing of loading the shear cracks initiated of the slab and other cracks from at the central increasing of loading the shear cracks initiated, see plate 3 and plate 4. In general, from the tested slabs under the monotonic loads, it is noticed that the angle of the failure zone decreases with increasing of the distance between the columns, while for the slabs tested under repeated loads, there is no uniform context of the relationship between the failure angle and distance between columns.

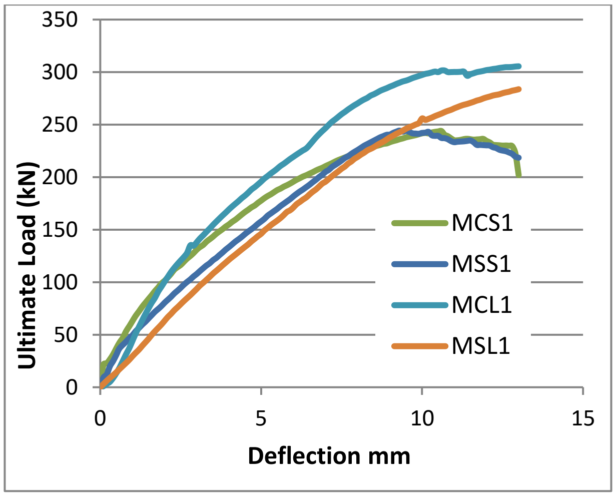

Fig.1. Load-deflection relationships for slabs with one column for different column section and size

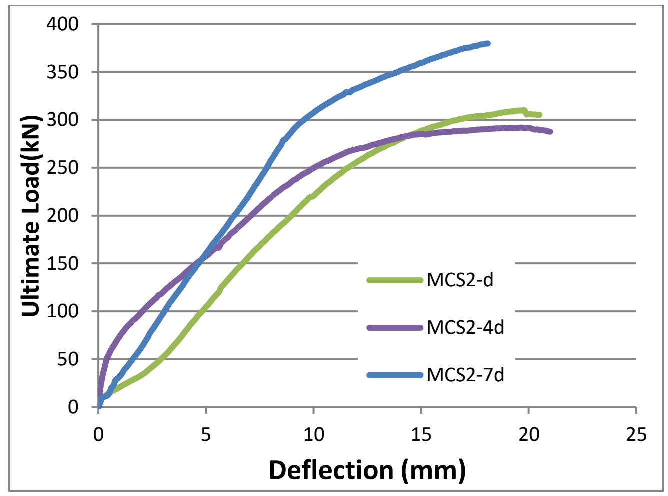

Fig.2 Load-deflection relation for slabs with a circle-smaller column for different column distances.

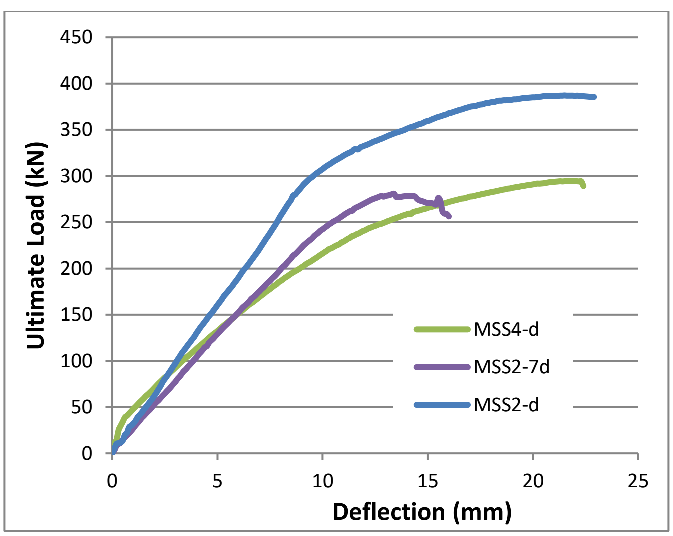

Fig.3 Load- deflection relation for slabs with a square-smaller column for different column distances

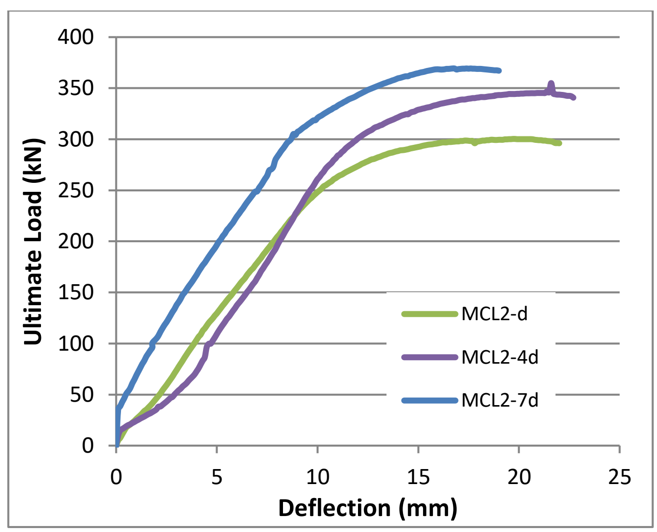

Fig.4 Load- deflection relation for slabs with a circle-bigger column for different column distances

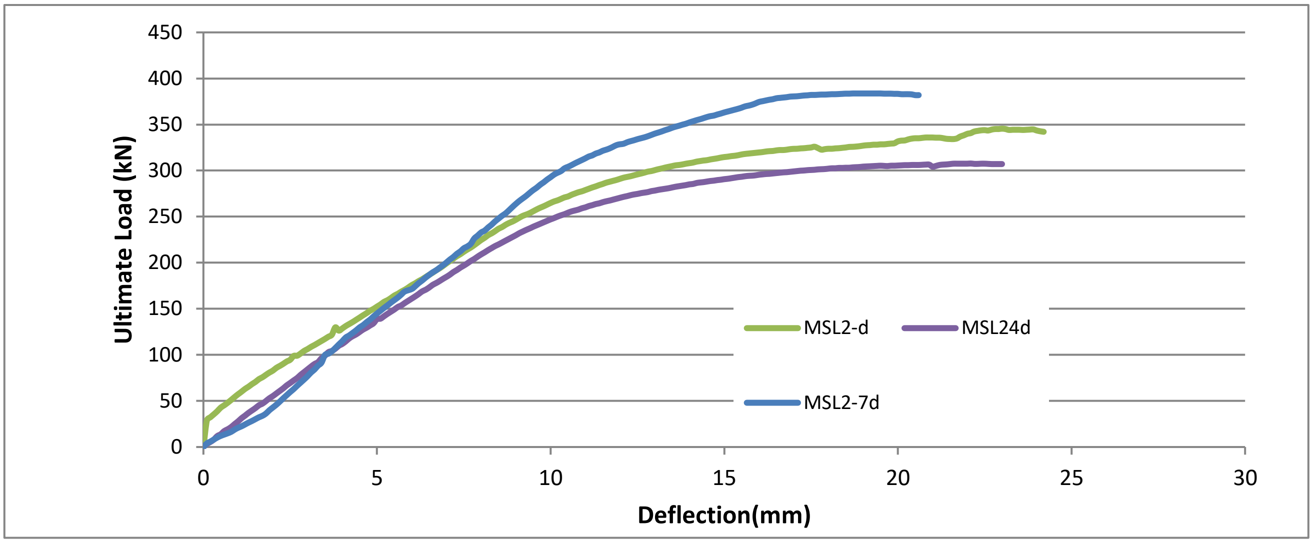

Fig.5 Load- deflection relation for slabs with square-bigger column for different column distances

Table 6

Test Result of Slabs specimen

Slab Designation	No of columns	Shape of column	Column Size (mm)	First Cracking load (KN)	Ultimate Load (P_u) (KN)	Max Deflection (mm)	Mode of Failure
MCS_1	One	Circular	85	100	244.3	10.9	Punching
MSS_1	One	Square	(75*75)	145	243.9	11.2	punching
MCL_1	One	Circular	113	150	308.9	20.6	Punching
MSL_1	One	Square	(100*100)	155	306.3	18.6	Punching
$MCS_{2\text{-}d}$	Two	Circular	85	144	310.1	19.8	Punching
$MCS_{2\text{-}4d}$	Two	Circular	85	120	291.9	19.6	Punching +Flexural
$MCS_{2\text{-}7d}$	Two	Circular	85	128	379.9	18.1	punching
$MSS_{2\text{-}d}$	Two	Square	(75*75)	105	294.3	21.3	Punching
$MSS_{2\text{-}4d}$	Two	Square	(75*75)	127	280.7	13.4	Punching
$MSS_{2\text{-}7d}$	Two	Square	(75*75)	132	287.1	21.5	Punching +Flexural
$MCL_{2\text{-}d}$	Two	Circular	113	133	300.3	19.7	punching
$MCL_{2\text{-}4d}$	Two	Circular	113	145	345.5	21.6	punching
$MCL_{2\text{-}7d}$	Two	Circular	113	140	369.3	16.7	Punching +Flexural
$MSL_{2\text{-}d}$	Two	Square	(100*100)	97.5	345.5	23	punching
$MSL_{2\text{-}4d}$	Two	Square	(100*100)	125	307.7	22.1	punching
$MSL_{2\text{-}7d}$	Two	Square	(100*100)	125	383.7	11.87	Punching+ Flexural

Plate.3. Crack Pattern for Slabs with one column.

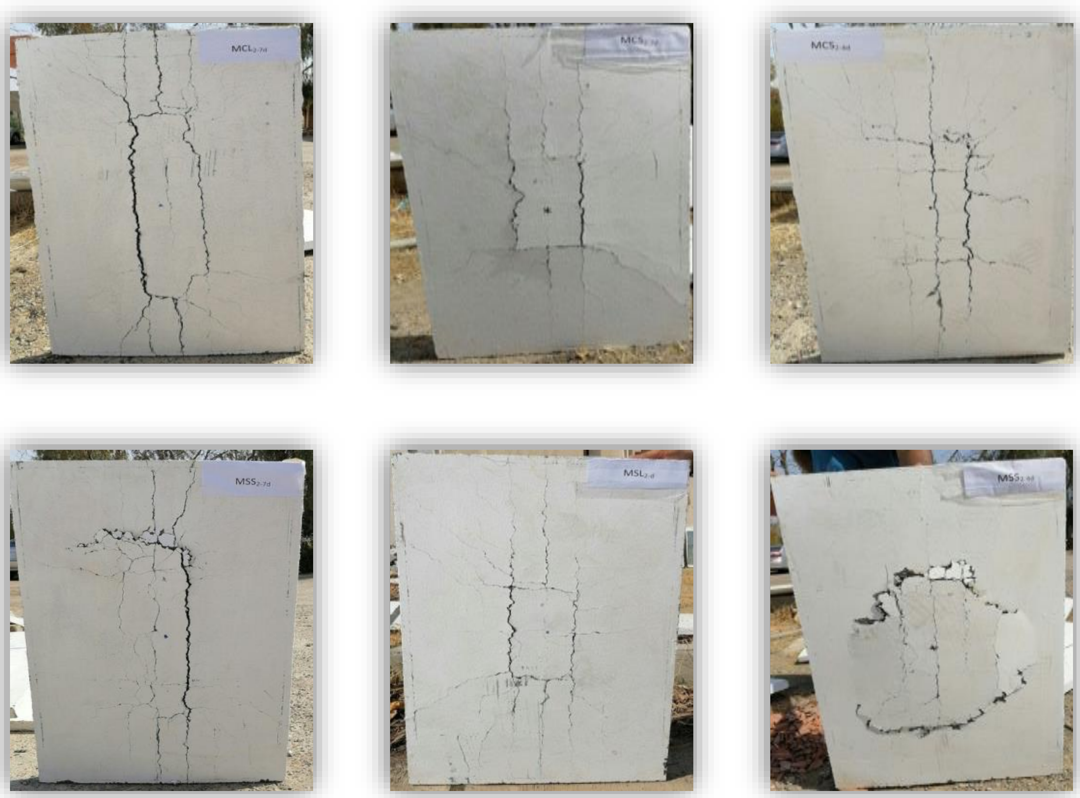

Plate.4. Crack Pattern for Slabs with two columns

6. CONCLUSIONS

Based on the results obtained from this experimental work, the following conclusions can be drawn:

1. The ultimate loads for slabs with circular column sections have slightly higher than those with square column sections for both columns section size. This difference in the ultimate load values happens because of stress concentration at square column corners so failure occurs faster.
2. Increasing column size will increase the ultimate load caused by punching shear failure for the ultimate column section shape.
3. The ultimate loads for slabs that have two columns are greater than those of slabs that have one column, and the ultimate load increase with increasing the distance between columns.
4. It is noticed that when the distance between the columns increases, the area, and perimeter of the failure area increase.
5. In general, it was noticed that the area of the failed zone subjected to repeated loading is smaller than that of the specimens under monotonic load.

6. In general, for the slabs tested under monotonic loading, the angle of the failure zone decreases with increasing of the distance between the columns.

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