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Experimental Study of Lightweight Concrete Flat Plate with Sandwich Shear Plates

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Abstract

The study presents an experimental investigation on the influence of embedded steel plate (sandwich) as shearhead reinforcement on the punching shear strength of reinforced light concrete flat plates.

Five half-scale models of slab-column connection of (1000 x 1000 x 70mm) simply supported along the four edges are tested. The slabs are loaded concentrically by a central stub column. The variables studied are; the thickness (2 and 4mm) and the dimensions (90mm x 150mm and 180mm x150mm) of steel plate. Results indicate that the effect of increasing of the thickness and steel plate dimensions, and shear connectors spacing improve the resistance to punching shear, enhance type of failure and increase the value of the ultimate load capacity. The ultimate load increases by about (47.57and 73.79%) of the maximum ultimate load for the plate thickness 2 and 4mm respectively while the spacing between the shear connectors is (d/2) and about (59.22 and 88.35%) for the thickness 2 and 4mm while the spacing between shear connectors is (d).

دراسة مختبريه للبلاطات المسطحة المصنوعة من الخرسانة الخفيفة الوزن مع صفائح القص المزدوجة

الخلاصة

يقدم هذا البحث دراسة عملية لتأثير استخدام تسليح القص الخاص المطمور (ساندوج) على مقاومة القص الثاقب للبلاطات المستوية المسلحة الخفيفة الوزن. خمسة نماذج أعدت بإبعاد (70x1000x1000) ملم ذات إسناد بسيط على طول حافاتها

الاربعه. كل البلاطات محمله مركزيا بواسطة عمود مرتبط مع السقف. المتغيرات التي تم دراستها هي: السمك (2و4) ملم والأبعاد (90*150 و180*150) ملم للصفائح الحديدية. أظهرت النتائج تأثير (زيادة السمك، أبعاد الصفيحة، مسافات الروابط القصية) على مقاومة القص الثاقب، شكل الفشل على البلاطة. وإن قيمة الحمل الأقصى يتراوح من (47،57 و 73،79%) عندما يكون سمك صفائح التقوية هي 2 و 4ملم على التوالي بينما المسافة بين الروابط القصية هي d/2 , وعندما كانت المسافات بين الروابط القصية d كانت الأحمال القصوى تتراوح (59،22 و 88،35%) لنفس سمك صفائح التقوية 2 و 4 ملم .

Introduction:

A shearhead is a separately definable structure embedded in the concrete at the junction, and serves to spread the load of the floor on the respective column and thereby reduces the effect of the vertical forces; i.e., reduces the stress in the slab concrete by increasing the critical punching shear perimeter around the column. Several types of shearheads are used in different countries such as:

1. Two pairs or single-crossed channel or wide flange steel sections.
2. Collars from steel channels (Giellinger shearheads).
3. Steel plate.

In the present study, the effect of embedded steel plates (sandwich) as shearheads reinforcement on the punching shear strength of lightweight concrete slabs is studied. The parameters studied are the dimensions and thickness of steel plates.

Maximum failure loads, deflection, failure characteristics of the tested slabs are taken into consideration and compared with those slabs without steel plates.

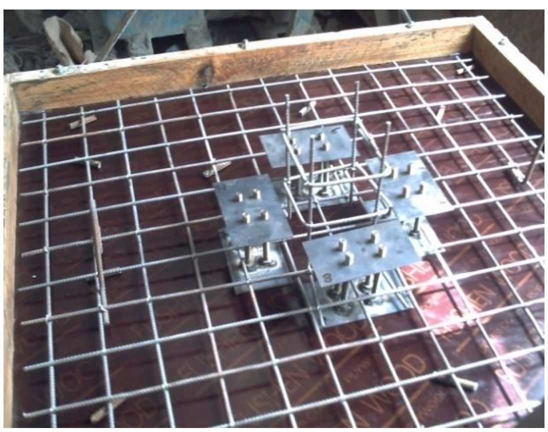
Experimental Investigation

Specimen preparation

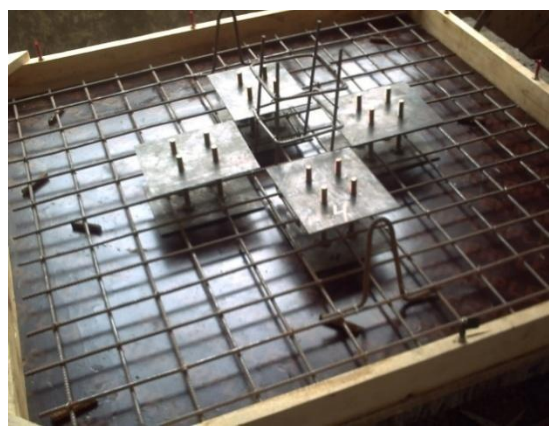
Five reinforced lightweight concrete flat plate were designed, instrumented and tested in displacement control mode. Details of these specimens are listed in table (1), and shown in Figure (1). Two different plate thicknesses are used as a shearhead and strengthening reinforcement as shown in Plate (1), one of which does not achieve punching resistance more than the reference specimen.

Table (1) Characteristics of the Tested Slabs

Specimens	Plate	Dimensions of steel plate(mm)	Spacing between shear connector(mm)	
			X-dir.	Y-dir.
LWR	—	—	—	—
LW1	A	90× 150× 2	30	50
LW2	B	180× 150× 2	60	50
LW3	A	90× 150× 4	30	50
LW4	B	180× 150× 4	60	50



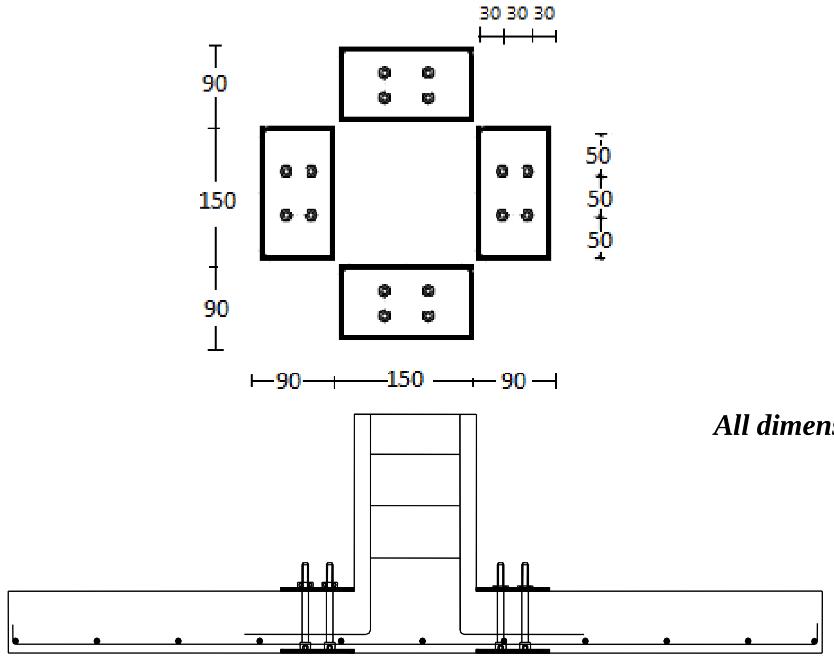
A- 90x150



B- 180x150

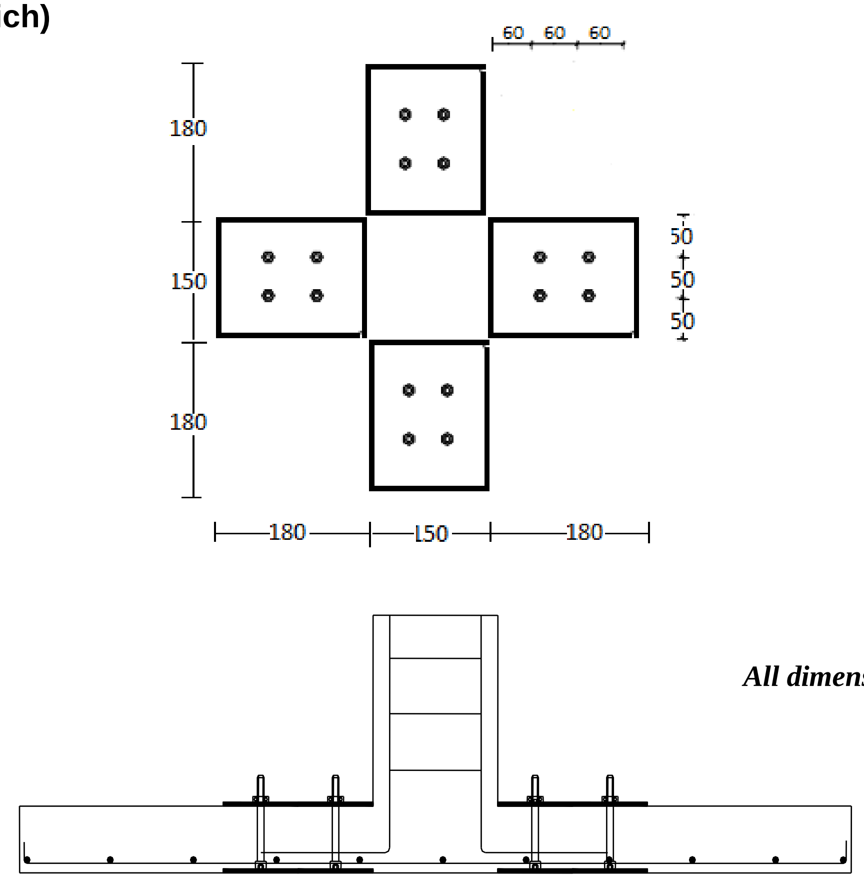
Plate (1) Shear connector welded to steel plate

All slabs are geometrically similar, having dimensions of (1000× 1000× 70 mm) and loaded through a central column of dimension of (150× 150× 200 mm). The slabs have the same flexural reinforcement. The slabs are simply supported along all edges and the distance from c/c of support is (900mm).



All dimensions are in mm

A- 4x90x150 Double steel plates (sandwich)



All dimensions are in mm

B- 4x180x150 Double steel plates (sandwich)

Figure (1) Type of reinforcement and details of shear connector

Materials

Cement

Ordinary Portland cement produced at northern cement factory (mass-Bazian) is used throughout this investigation. Analysis of chemical composition and physical properties of this cement are made at the National Center of Construction Laboratories and Research. Results show that the cement conforms to the Iraqi specification No. 5/1984(1).

Fine Aggregate

Normal weight, natural sand brought from (AL –Akhaidher) area, is used as fine aggregate. The grading of sand is conformed to the requirements of the Iraqi specification No.45/1984(2) zone 2.

Light Weight Coarse Aggregat:

Local naturally stone (porcelinite stone) is used as coarse aggregate in product of light weight concrete. The required quantity of porcelinite stone is brought and tested with the help of the State Company of Geological Survey and Mining. The quarry of this stone is located in Trefawi area (Rutba) at the western desert in Anbar governorate. The lumps are firstly crushed into smaller size manually by means of a hammer in order to facilitate the insertion of the lumps through the feed opening of the crusher machine. The Jaw crusher is setup to give a finished product of about 12.5 mm maximum aggregate size. The grading of coarse porcelinite aggregate is within the limits of ASTM C330-2003(3).

Water

Ordinary tap water was used for mixing and curing all the concrete specimens used in this research.

Steel Reinforcement:

Welded wire fabric mesh is used as flexural reinforcement placed in the tension face of the slabs. The average yield strength is (577MPa), and the average ultimate strength is (696MPa). The deformed wires are (6mm) in diameter at (75mm) c/c spacing each way in tension face. The test is made in the Material laboratory, College of Engineering, AL-Mustansiriya University.

Steel Plate

The thicknesses of steel plate are (2 and 4 mm) tested in the materials laboratory at the College of Engineering, Al-Mustansiriya University. Steel strip is made with (30 mm) width and length (400 mm). The yield strength and ultimate strength are shown in Table (2).

Table (2) Yield Strength and Ultimate Strength of Steel Plate.

No.	Thickness (mm)	Yield Strength (MPa)	Ultimate Strength (MPa)
1	2	243	307
2	4	312	398

Shear Connectors:

Mechanical shear connectors (steel bolt) are used in all samples. The bolts (shear connectors) are connected to the steel plate by using welding. In order to determine the mechanical properties of the steel bolt, a series of tests is conducted on random specimens (i.e. direct shear tests). The results of tensile tests and shear tests are given in Table (3).

Table (3) Test Results of Threaded Steel Bolt

Steel specimens	*Measured diameter (mm)*		*Yield tensile Strength (N/mm^2)*	*Ultimate tensile force (kN)*	*Ultimate tensile Strength (N/mm^2)*	*Ultimate shear force (kN)*
	Inner	*Outer*				
(Shear connector)	*8.51*	*9.6*	*353.12*	*33.5*	*589.27*	20.075

Superplasticizer

The superplasticizer used in this study is Glenium 51, which is free from chlorides and complies with ASTM C 494 Types A and F.

Mix Design and Proportions

The control mix proportions of 1: 0.91: 0.945 (cement: sand: porcelinite), and water/ cement ratio of 0.39 and superplasticizer content of 1% by weight of cement were used, as listed in Table (4). This mix gave average concrete cube strength of 25.42 N/mm^2 at 28 days.

Table (4) Details of Mixes Used in Slabs

Cement content (kg/m^3)	*Aggregate content*		*Porcelinite content (kg/m^3)*	*Water content (kg/m^3)*	*s.p% by weight of cement*	*w/c ratio*	*Average cube compressive strength (N/mm^2)*	*Density of concrete (kg/m^3)*
	Sand (kg/m^3)	*Gravel (kg/m^3)*						
550	*500*	*-*	*520*	*214*	*1*	*0.39*	*25.42*	*1860*

The concrete was mixed by using a horizontal rotary mixer with (0.19 m^3) capacity available in the structures laboratory, College of Engineering, Al-Mustansiriya University.

Moulds

The moulds used for casting the slab specimens are plywood moulds with (16 mm) thickness of board. The mould consists of a bed and a moveable side and the sides are fixed to the bed by long screws. The clear dimensions of moulds are (1000× 1000× 70 mm). In addition, the mould of the column has of two steel angles fixed together by bolt and fixed in the center of the slab by four arms in each side, as shown in Plate (2).

Curing and Age of Testing

After (24) hours, the control specimens were stripped from the moulds and cured (kept) in water bath for (28) days with almost constant laboratory temperature. Before (24) hours, the specimens were taken out of the water bath and paint with white color. Then tested done accordance with the standard specifications.

Mechanical Properties of Concrete:

Cylindrical (150x300) and cube (150) specimens are used to test the compressive strength of concrete. The compressive test is done according to ASTM C39(4) and B.S 1881(5), respectively.

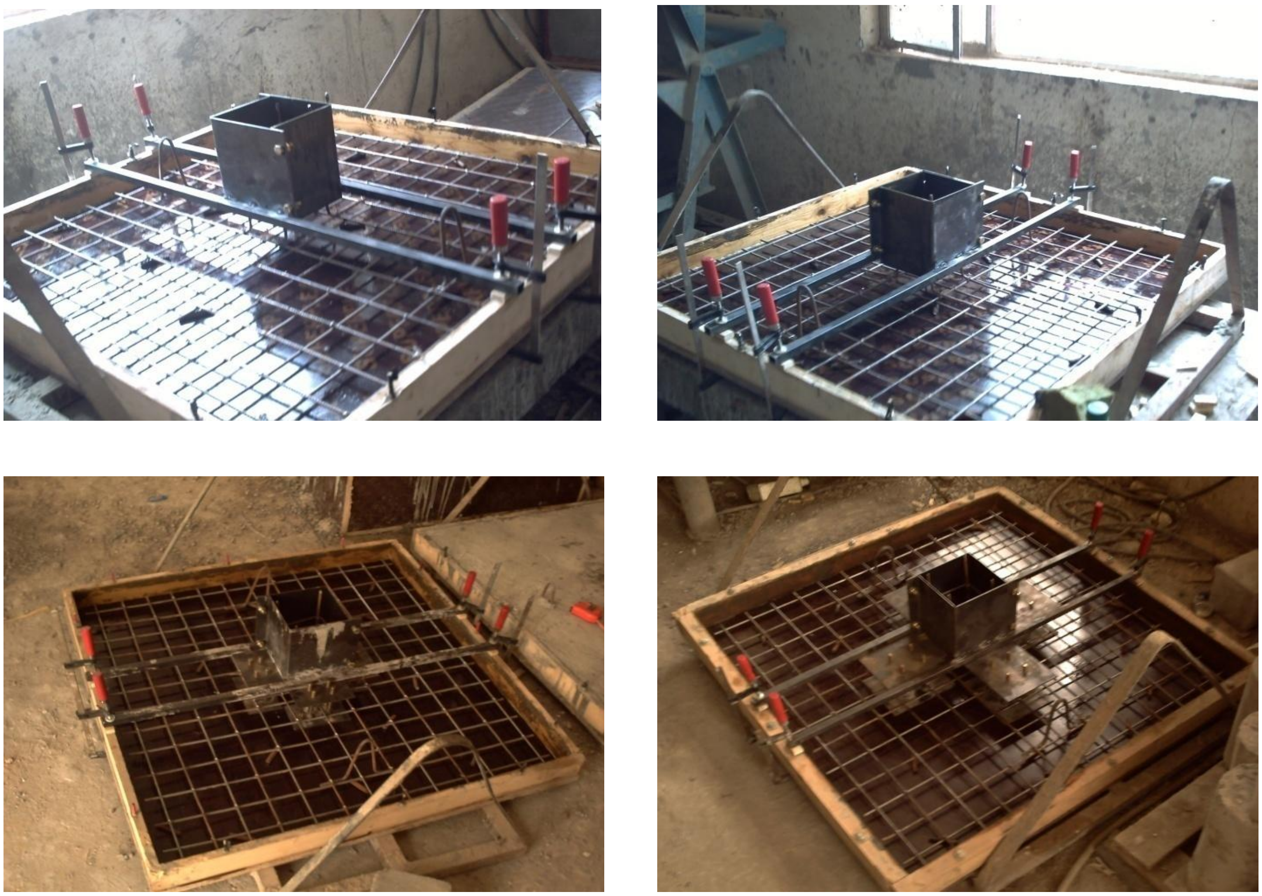


Plate (2) Slab Mould

Measurements of the static modulus of elasticity were made according to ASTM C469-2003(6) at 40% of the ultimate load, using (150× 300mm) concrete cylinder tested in compression.

Splitting tensile strength test was performed on a (150×300 mm) concrete cylinders according to the ASTM C496-2003 [7].

A prism of (500× 100× 100 mm) under third-point loading[8] is used to determine the modulus of rupture.

The results of mechanical properties of lightweight concrete are shown in table (5).

Table (5) Mechanical Properties of Concrete

Specimens	Average Cube Strength f_{cu} (MPa)	Average Cylinder Strength f_c\` (MPa)	Average Measured Static Modulus of Elasticity GPa	*Measured Average Splitting Tensile Strength (MPa)*	*Measured Modulus of Rupture (MPa)*
LWR	27.78	19.18	15.21	1.344	1.75
LW1	27.00	20.65	14.98	1.67	1.625
LW2	24.56	21.22	14.81	1.514	2.00
LW3	23.89	20.09	15.06	1.627	2.00
LW4	23.89	20.37	15.27	1.584	1.75

Test setup

The machine used in the tests is a universal hydraulic machine with (3000kN) capacity available in the structural engineering laboratory, in the College of Engineering, Al- Mustansiriya University. The loading arrangement with loading frame is shown in Plate (3).

Special frame is manufactured to be used to support the specimens. It consists of square frame (Figure (2)) made from double (C-Section) 100x50x6mm welded to gather to increase the rigidity and raise the tested slab to provide space for measuring devices.

Loading frame is made from two channels (C-Section) 300x105x15mm welded back to back to distribute the load of the hydraulic jack between the balancing support and the test slab, as shown in Figure (2).

The deflection measurement is taken at several points. Five dial gages of (0.01mm) sensitivity are mounted on a steel frame, at the centre of slab, column edge, center of plate, outer plate edge and d or d/2 from plate edge. Plate (4) and Figure (3) show the arrangement and positions of dial gages respectively.

Plate (3) Testing Machine with Loading Frame

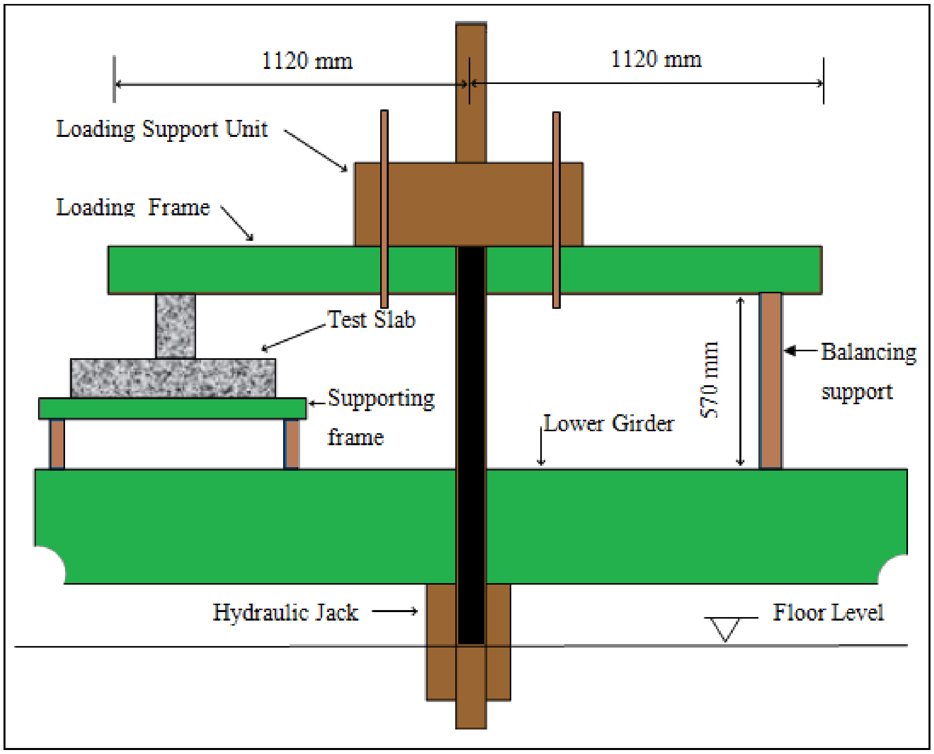


Figure (2) Simple Sketch for the Loading Frame

Plate (4) Deflection Measurement at Tension Face of Specimens

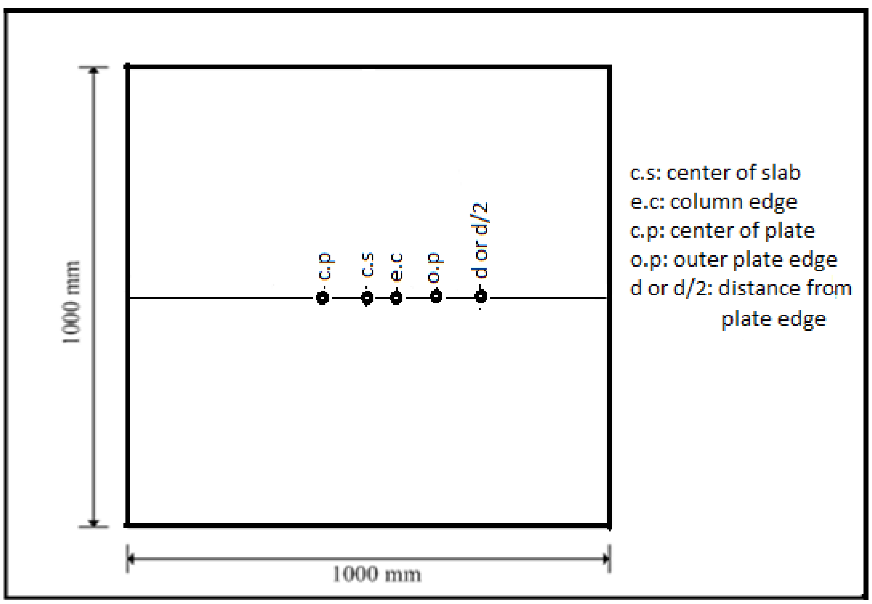


Figure (3) Positions of Dial Gages

Result and Discussion

Crack Pattern and Failure Mode

The results of first crack and ultimate loads of slabs are illustrated in Table (6).

Table (6) First Crack and Ultimate Loads of Slabs.

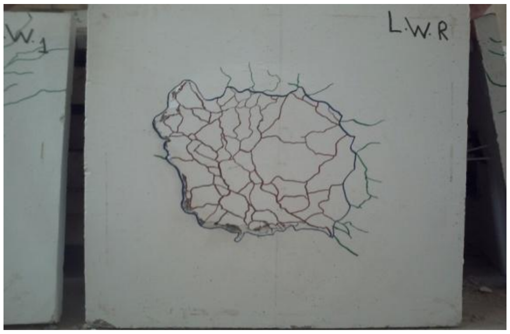
Slab	*First crack load (Pcr) (kN)*	*Increasing in (Pcr.) %*	*Ultimate Load (Pu) (kN)*	*Increasing in(Pu) %*	$\frac{Pcr}{Pu}$ *(%)*	*Deflection at ultimate load at center (mm)*	*Mode of failure*
LWR	*21*	*-*	*103*	*-*	*20.39*	*13.3*	*Punching*
LW1	*24.5*	*16.67*	*152*	*47.57*	*16.12*	*11.8*	*Punching*
LW2	*23*	*9.52*	*164*	*59.22*	*14.02*	*17.45*	*Flexural*
LW3	*25*	*19.05*	*179*	*73.79*	*13.97*	*17.5*	*Punching*
LW4	*25*	*19.05*	*194*	*88.35*	*12.89*	*20.2*	*Flexural*

When load is applied to these slab specimens, the first crack is formed at about (12.89-20.39) % from the ultimate load for each slab.

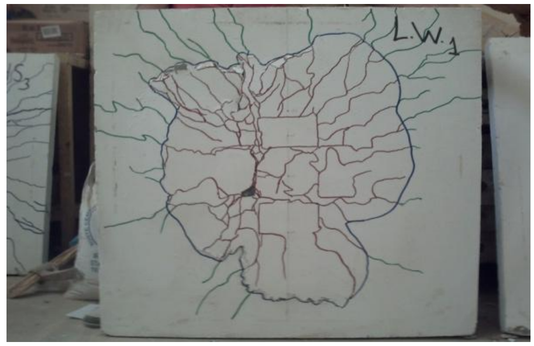
The first crack appears around the sides of the column on the tension face of the slab without steel plate. On the other hand, the first crack of all tested slabs with steel plate appears in the tension face of the slab near one or more of the corners of steel plate, and the remaining cracks form at the central region of the slab and propagate towards the edge of the slab. By increasing the load, these cracks widen and increase in number. Plate (5) illustrates crack patterns and failure modes.

Load – Deflection Behavior

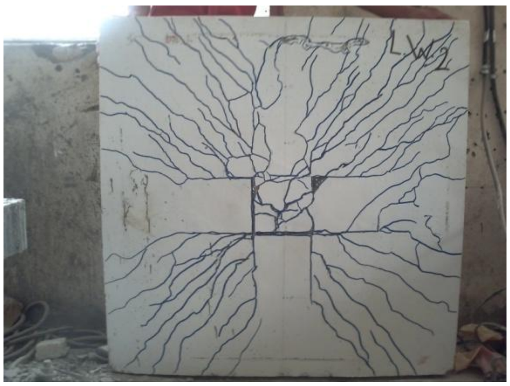
The deflection results are illustrated in Table (7). The test results show that, the maximum deflection at ultimate load occurs when the plate thickness is equal to (4mm) and spacing between shear connectors is (d) (slab LW4), and the deflection at the ultimate load increases when the distance between shear connectors is increased or the thickness of plates is increased. Figures (4) to (8) show the load-deflection relationship of the slabs. Notice that the ductility of the all specimens increased except in (LW1) which slightly decreased comparison with reference slab. Test results are listed below:



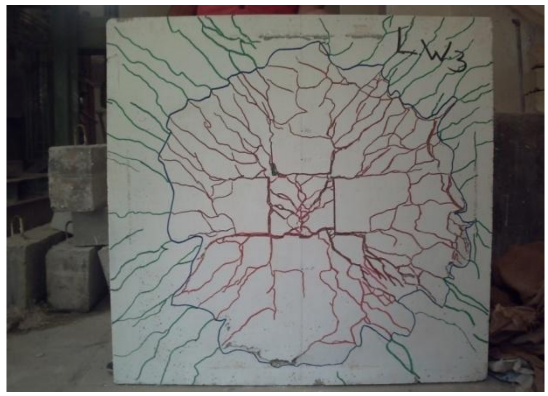
LWR



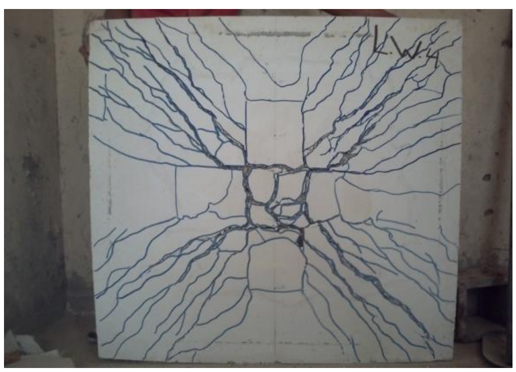
LW1



LW2



LW3



LW4

Plate (5): Crack Patterns (Bottom Face)

1- In **(**LW1 and LW2**)**, both LW1 and LW2 are provided with the same sandwich plates thickness (2mm) but different in spacing between shear connectors and length of plates. Using sandwich reinforcement (LW2) increases the deflection by about (31.20%) and (LW1) decreases the deflection by about (11.28%) in comparison with reference slab (LWR). (LW2) is more deflection than (LW1) by about (47.88%), as shown in Figure (4).

2- In (LW1 and LW3), both LW1 and LW3 are provided with the same spacing between shear connectors and dimension of sandwich plates except thickness (2 and 4mm) respectively. (LW3) increases the deflection by about (31.58%) and (LW1) decreases the deflection by about (11.28%) in comparison with reference slab (LWR). (LW3) is more deflection then (LW1) by about (48.31), as shown in Figure (6).

3- In **(**LW2 and LW4**)**, both LW2 and LW4 are provided with the same spacing between shear connectors and dimension of sandwich plates except thickness (2 and 4mm) respectively. (LW2and LW4) increases the deflection by about (31.20 and 51.88%) respectively, in comparison with reference slab (LWR). (LW4) is more deflection than (LW2) by about (15.76%), as shown in Figure (7).

4- In **(**LW3 and LW4**)**, both LW3 and LW4 are provided with the same sandwich plates thickness (4mm) but different in spacing between shear connectors and length of plates. (LW3 and LW4) increases the deflection by about (31.58 and 51.88%) respectively, in comparison with reference slab (LWR). (LW4) is more deflection than (LW3) by about (15.43%), as shown in Figure (5).

Table (7) Load-Deflection of Slabs

Slab	*Deflection at first crack (mm)*					*Deflection at ultimate load (mm)*				
	Under Slab center	*column edge*	*Plate center*	*outer Plate edge*	*At D or d/2 from plate edge*	*Under Slab center*	*column edge*	*Plate center*	*outer Plate edge*	*At D or d/2 from plate edge*
LWR	*1.46*	*1.44*	*-*	*-*	*1.37*	*13.3*	*13.59*	*-*	*-*	*13.4*
LW1	*1.84*	*1.76*	*1.9*	*1.58*	*1.92*	*11.8*	*11.41*	*9.14*	*9.59*	*9.64*
LW2	*2.5*	*2.6*	*2.29*	*2.05*	*1.92*	*17.45*	*17.9*	*13.38*	*11.6*	*8.15*
LW3	*1.45*	*1.51*	*1.23*	*1.52*	*1.04*	*17.5*	*18.62*	*14.7*	*14.65*	*12.38*
LW4	*1.66*	*1.81*	*1.31*	*1.5*	*0.8*	*20.2*	*21.1*	*23.5*	*12.28*	*8.90*

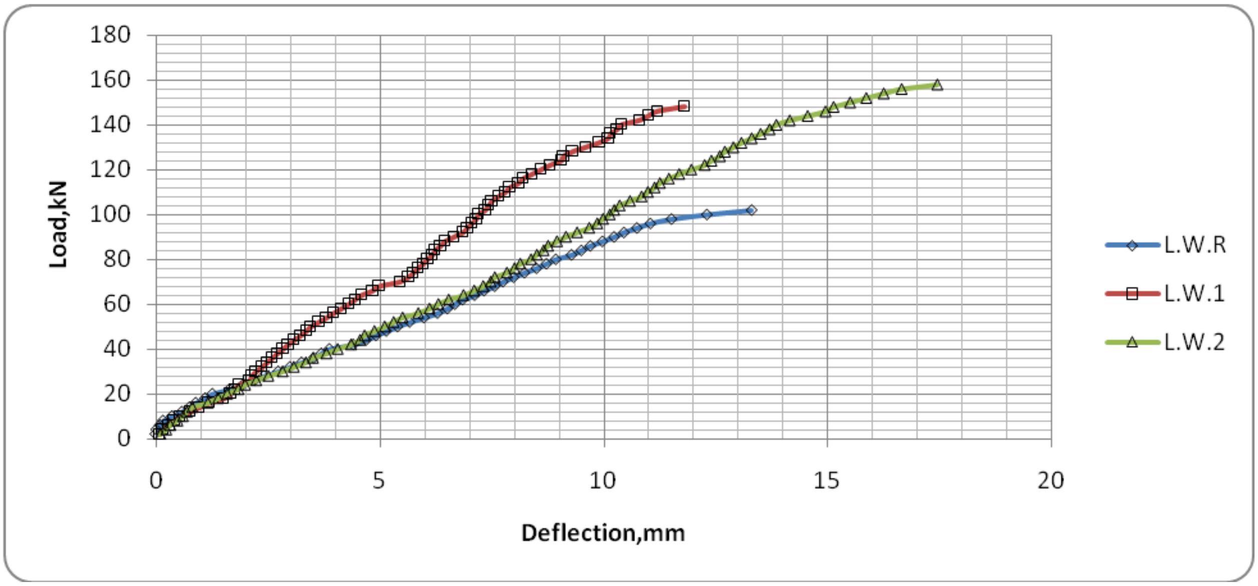


Figure (4) Effect of steel plate thickness (2mm) on the Load –Deflection at center of Slab

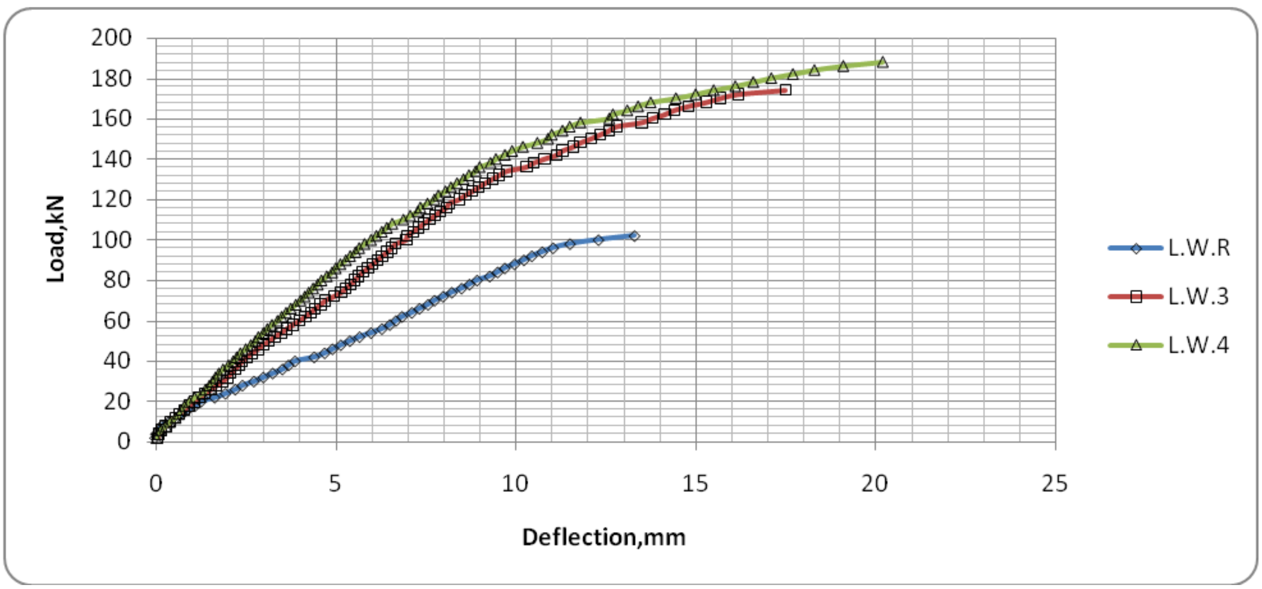


Figure (5) Effect of steel plate thickness (4mm) on the Load –Deflection at center of Slab

Ultimate Load

The observed failure loads of the tested slabs are shown in Table (6). Test results are listed below:

1- In (LWR), the punching shear failure occurs at the lower loads than the other slabs with steel plate sandwich. The test results show that the slabs (LW1, LW2, LW3 and LW4) give increasing in strength than the reference slab (LWR) by about (47.57, 59.22, 73.79 and 88.35 %) respectively.

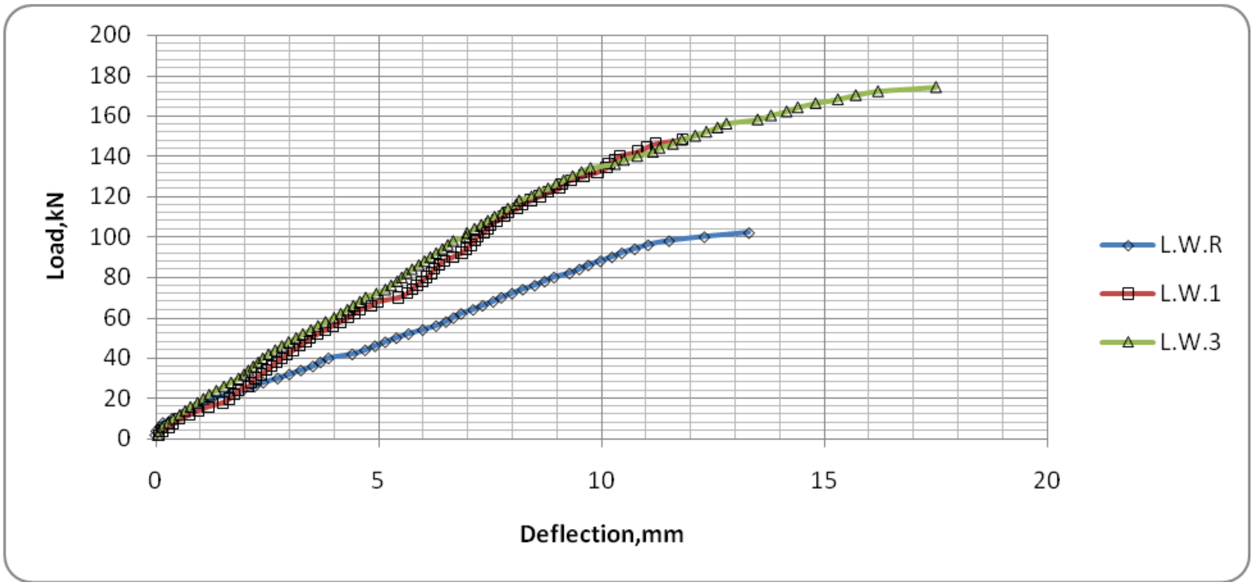


Figure (6) Effect of steel plate (90x150) on the Load –Deflection at center of Slab

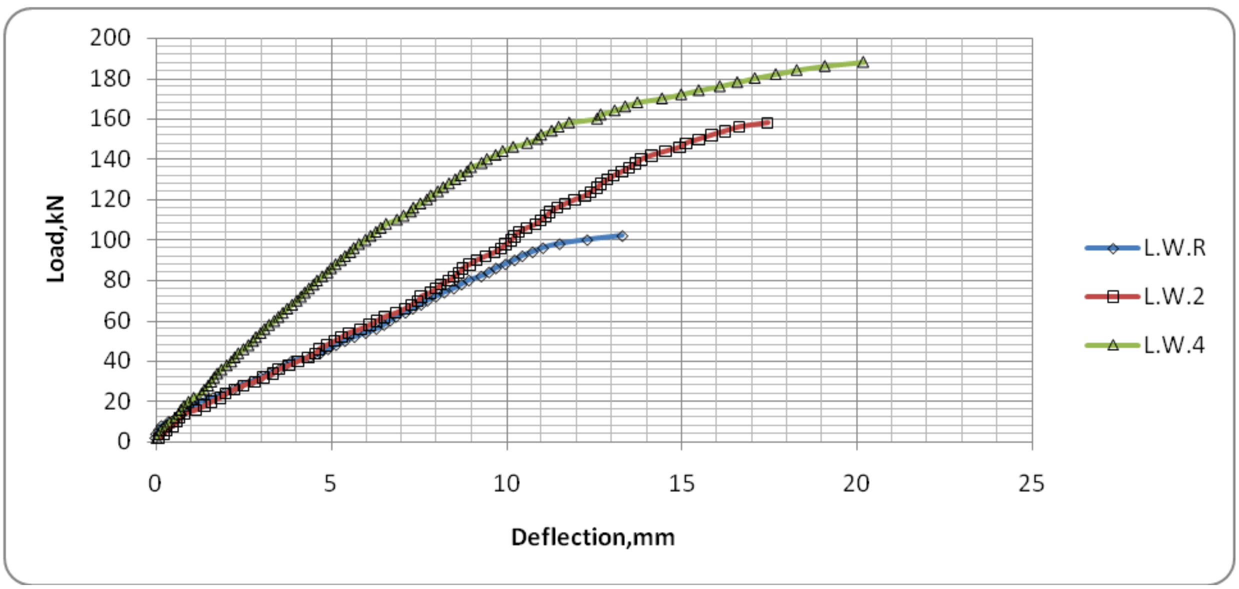


Figure (7) Effect of steel plate (180x150) on the Load –Deflection at center of Slab

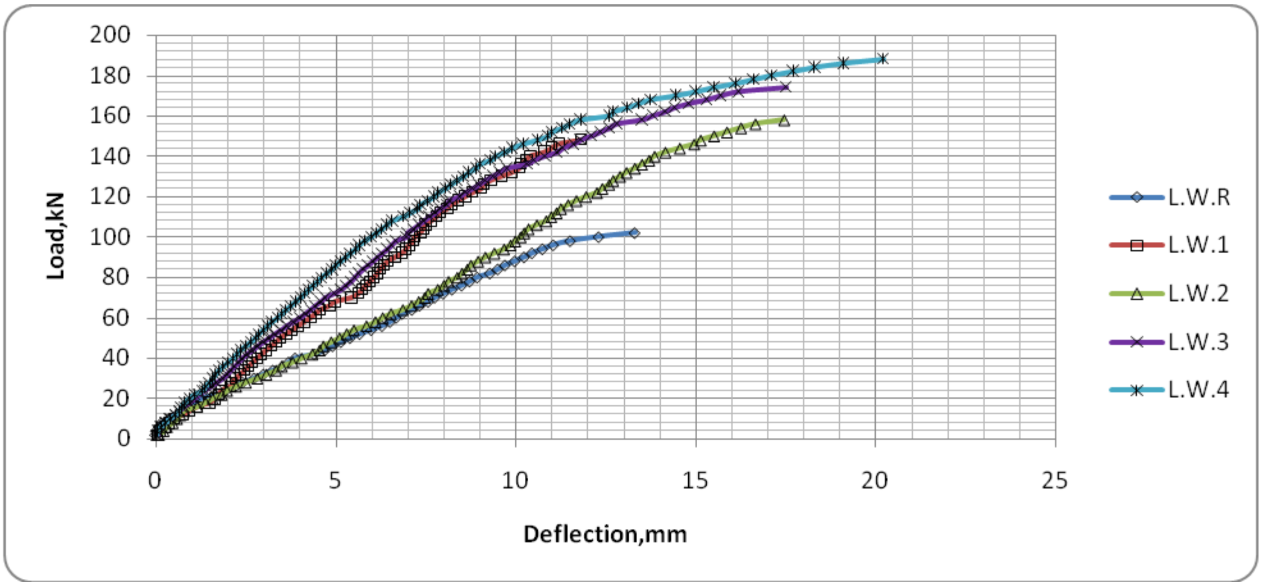


Figure (8) Load –Deflection Curve for all slabs

2- In **(**LW1 and LW2**)**, both LW1 and LW2 are provided with the same sandwich plates thickness(2mm) but different in spacing between shear connectors and length of plates. The increasing in the ultimate load of (LW2) is about (7.89) %, in comparison with (LW1).
3- In (LW1 and LW3), both LW1 and LW3 are provided with the same spacing between shear connectors and dimension of sandwich plates except thickness (2 and 4mm) respectively. The increasing in the ultimate load of (LW3) is about (17.76) %, in comparison with (LW1).
4- In **(**LW2 and LW4**)**, both LW2 and LW4 are provided with the same spacing between shear connectors and dimension of sandwich plates except thickness (2 and 4mm) respectively. The increasing in the ultimate load of (LW4) is about (18.29) %, in comparison with (LW2).
5- In **(**LW3 and LW4**)**, both LW3 and LW4 are provided with the same sandwich plates thickness(4mm) but different in spacing between shear connectors and length of plates. The increasing in the ultimate load of (LW4) is about (8.38) %, in comparison with (LW3).

Figure (9) shows the variation of the ultimate punching shear capacity for all slabs.

Critical Section Perimeter

According to ACI (318-11) [9] and BS (8110-97) [10] codes, the critical section perimeter is assumed to be at (d/2) and (1.5d) from the column face respectively.

For the slabs without steel plate, the critical section perimeter is considered as half the distance (x) between the column face and the end of the actual punching failure surface on the tension side of the slab. While, it considered as half the distance (x) between the steel plate and the end of the actual punching failure surface for the slabs with steel plate. The calculated distance is based on the measured area. Figure (10) shows the method used to calculate critical sections for the tested slabs in this study. Table (8) listed the calculated distances.

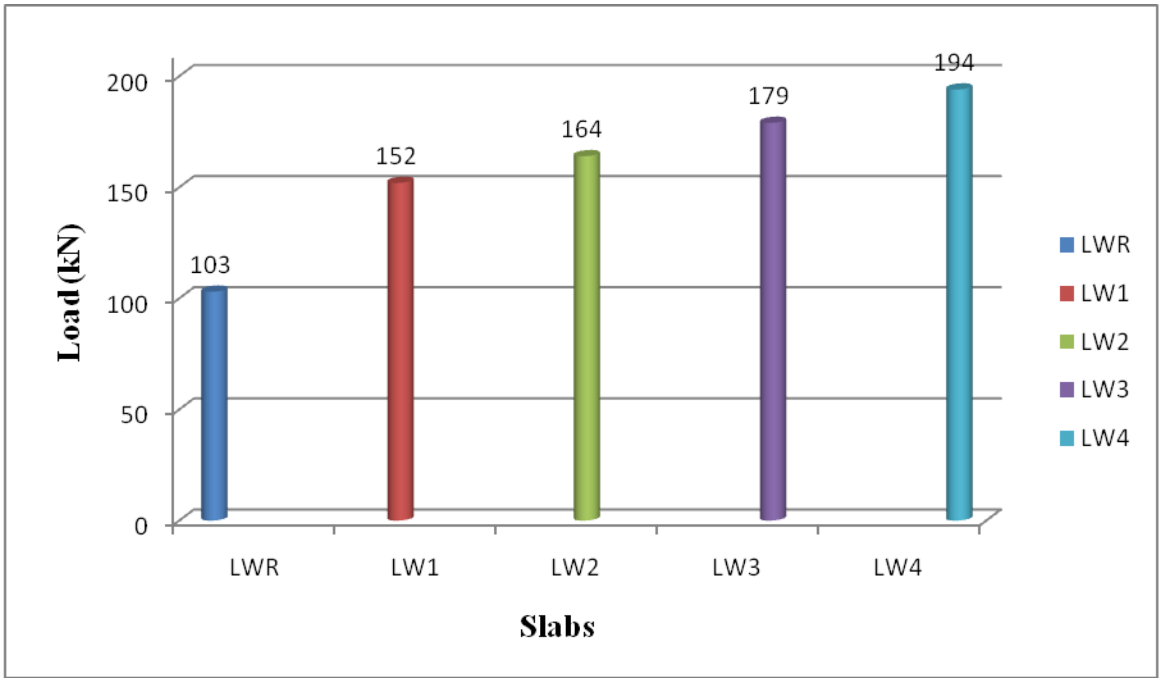


Figure (9) Variation of the Ultimate punching shear capacity for different slabs

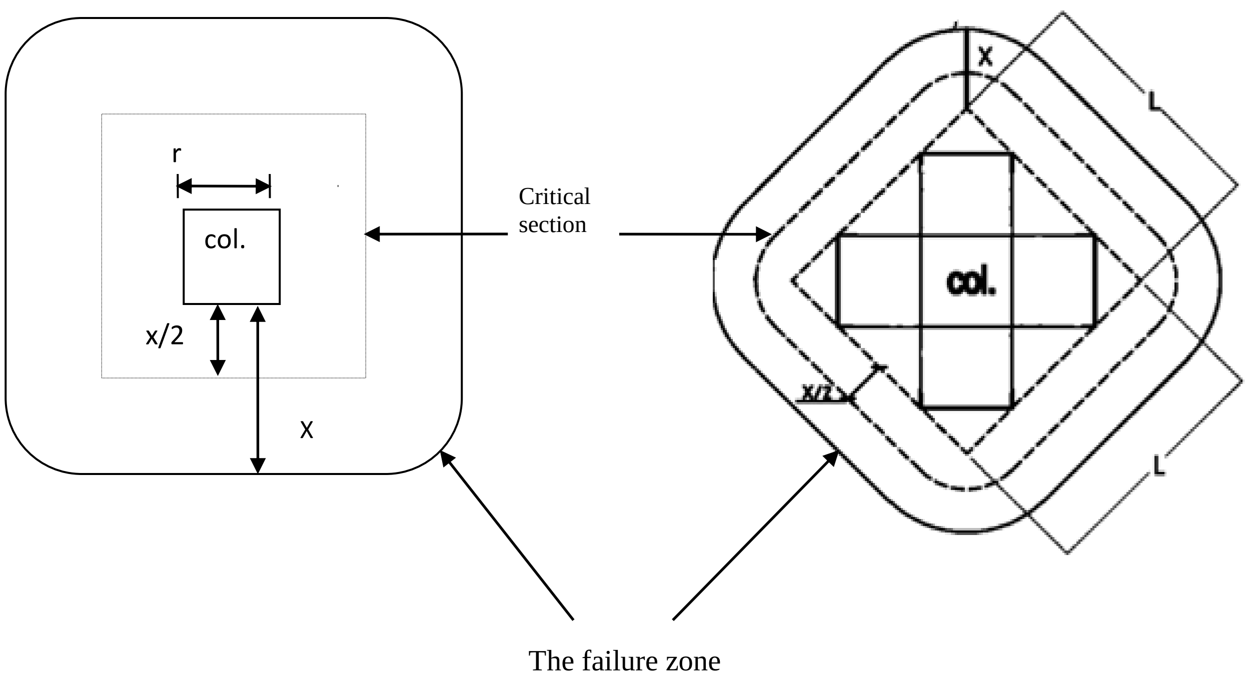


Figure (10) Method Used to Calculate the Critical Sections.

Table (8) Calculation of X distances in the reinforced concrete slabs.

slab	*Measured area (mm^2)*	*X (mm)*	*X/2 (mm)*	*Critical perimeter at X/2 (mm)*	*Increase in perimeter% comparing with Reference*
LWR	*187205*	*152.59*	*76.30*	*1210.36*	-----
LW1	*393516*	*151.73*	*75.87*	*1964.56*	*62.31*
LW2	-----	-----	-----	-----	-----
LW3	*511129*	*199.52*	*99.76*	*2155.72*	*78.11*
LW4	-----	-----	-----	-----	-----

From the Table (8), it is found that a steel plate increases the critical section perimeter, this increases reaches about (62.31 and 78.11 %) respectively in (LW1and LW3) as compared with (LWR).

Ultimate Shear Stress

Shear stress is found to be reduced by a noticeable magnitude in reinforced concrete slabs with embedded sandwich as compared with reference slab (LWR) and the percentage of decrease reaches about (2.01%), due to the increase in punching shear perimeter, as shown in Table (9).

The results show that, the increase in thickness of steel plate from (2mm) to (4mm), with the same dimension, increases the ultimate shear stress about (7.35%) due to the increase in ultimate load.

Table (9) Shear Stress Characteristic in Tested Slabs.

Slab	*Calculated perimeter at X/2 (mm)*	*Ultimate load (kN)*	*Ultimate Shear Stresses (MPa)*	*% Decreasing in ultimate Shear Stresses comparing with reference slab (R)*
LWR	*1210.36*	*103*	*1.49*	------
LW1	*1964.56*	*152*	*1.36*	*8.72*
LW2	-----	*164*	-----	-----
LW3	*2155.72*	*179*	*1.46*	*2.01*
LW4	-----	*194*	----	-----

Conclusions

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

- The first crack appears around the sides of the column on the tension face of the slab at about (12.89- 20.39) % of the ultimate load, and later other cracks appear 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.
- The slabs (LW1, LW2, LW3 and LW4) give an increase in ultimate load over the reference slab (LWR) by about (47.57, 59.22, 73.79 and 88.35 %) respectively.
- The ultimate load has the maximum value when the plate thickness 4mm and spacing between shear connector is (d) in (LW4)
- Increases the deflection at ultimate load in slabs (LW2,LW3 and LW4) by about (31.20, 31.58 and 51.88) % respectively and decrease the deflection at ultimate load in slab (LW1) by about (11.28)% compared with reference slabs (LWR).
- The Slab with spacing between shear connector equal to (d/2) and steel thickness of (2 and 4mm)(LW1 and LW3), the increasing in size of failure zone is about (110.21 and 173.03)% and the increasing in the critical section perimeter is about (62.31and 78.11)% respectively, compared with reference slab (LWR).
- The ultimate shear stress decrease in slabs (LW1 and LW3) by about (8.72 and 2.01) % respectively, compared with reference slabs (LWR).

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