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Effect of Cross Section Properties on Flat Plate Behavior

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Abstract

On the wise of structural advantages of flat plate slab systems, the researches still deal with punching shear hazards and solution techniques for adopting a rational design comes from experimental investigations. Beside that there is a rapid development in production the high performance concretes using chemical additives and wide spectrum of different features fibers which avail additional options for the structural designers.

The present work is an experimental study adopts the comparison between uniform concrete sections with specific strength and hybrid sections (consists of two different layers with different strength in the top half and the bottom one) to provide reinforced concrete flat plate slabs and conclude the more advantage option for improving their behaviors against eventual punching shear failure. Normal strength, high strength and fibrous concrete with (34, 48 and 21) MPa compressive strength respectively are used to produce the slabs in this study.

The results revealed the preference of the high strength uniform section in improving the slab behavior besides increasing its ultimate load twice in comparison with a hybrid section contains high strength concrete at the top half only and there is no advantage from increasing the tension zone strength on the hybrid section slab behavior except the ductility.

Keywords: flat plate, punching shear, uniform section, hybrid section.

تأثير خواص المقطع العرضي على سلوك اللوحة المستوية

الخلاصة

على صعيد المزايا الإنشائية لمنظومات بلاطات الألواح المستوية، لاتزال الأبحاث مستمرة بخصوص مخاطر القص الثاقب وسبل معالجته لغرض الخروج بتصميم مقبول اعتماداً على التجارب العملية. وإلى جانب ذلك فإنّ التطور السريع في إنتاج الخرسانات عالية الأداء باستخدام المضافات الكيميائية وطيف واسع من الألياف ذات الصفات المتباينة يوفر خيارات إضافية للمصممين الإنشائيين.

تعتمد الدراسة الحالية على مبدأ المقارنة بين النتائج العملية لمقاطع موحدة ذات مقاومة معينة ومقاطع مهجنة تختلف فيها المقاومة بين النصفين الأعلى والأسفل استخدمت لإنتاج بلاطات خرسانية مسلحة على هيئة ألواح مستوية لغرض استنتاج الخيار الأفضل لتحسين سلوك تلك البلاطات تجاه فشل القص الثاقب. استخدمت خرسانة اعتيادية وخرسانة عالية المقاومة وأخرى ليفية بمقاومة إنضغاط قيمتها (34، 48 و 21) نت/ملم2 لإنتاج البلاطات في هذه الدراسة.

كشفت النتائج المختبرية أفضلية المقاطع الموحدة ذات المقاومة العالية في تحسين سلوك البلاطات إلى جانب زيادة حمل البلاطة الأقصى مرتين بقدر الزيادة المستحصلة من زيادة مقاومة منطقة الانضغاط للبلاطة مهجنة المقطع وكذلك فلا فائدة من زيادة مقاومة منطقة الشد في تحسين تصرف البلاطة مهجنة المقطع في ما عدا تحسين خاصية المطيلية.

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1. Introduction

Despite of attaining the flat plate structure many advantages over other slabs due to elimination of beams and girders, and resulting in: reduction in loads, diminishing of storey height, saving in construction works and aesthetically pleasant appearance, as in Figure 1; however, the critical issue is the two way shear because of high shear stress around the column-slab connection which leads to a brittle local failure in form of column punching through the slab along a truncated cone caused by a diagonal cracking (Regan, 1990).

The hazard of punching shear failure, as in Figure 2, can be avoided by: provision beams between the columns, thickening the slab around the columns (drop panels), or flaring the columns under the slabs (column capitals) (Alander, 1987). Whilst with flat plate system there are no drop panels or column capitals at the slab-column connections.

Many techniques are adopted in designing the flat plate systems to transform the failure mode from sudden (punching shear) to ductile (yielding of tension reinforcement). These techniques can summarized as: using high strength concrete for improving the punching shear resistance through the slab-column connection (Tuan, 2001), using steel fibers as shear reinforcement where its random dispersion in the conventional concrete offers a convenient and practical improvement in many concrete properties such as tensile strength, compressive strength, flexural strength, impact resistance and first crack and ultimate loads (Al-Ani, 1985), and many types of shear reinforcement have been used successfully for slab-column connections (Wolsiefer, 1984) such as: shearheads, bent-up bars, stirrups, shear studs, hooked bars and welded-wire fabric.

1.1 Flexural Failure

A common method for determination the flexural capacity of concrete slabs is yield line theory by Johansen (Johansen, 1962) in 1948. In this analysis, the critical factors are the slab reinforcement distribution, the slab ductility, and the conditions at the ultimate load (Harris, 2004). A generic representation of a probable collapse mechanism, involving formation of plastic hinges, for a simply supported square slab with a uniformly distributed load is shown in Figure 3.a.

1.2 Punching Shear Failure

Punching shear failure is a three dimensional problem due to the high shear stress in concrete. The punching crack is generated at: 30, 45, 60 and 90 degree inclinations to the middle plane of the slab. This crack is initiated by coalescence of micro-crack at the top of the slab. Those micro-cracks are formed across the slab thickness before failure occurs. At failure, the crack reached the slab-column intersection corner, the inclined punching shear failure surface takes place in the shape of truncated cone surrounding the column as Figure 4.

1.3Flexural Punching Shear Failure

A combination of flexural failure and punching shear failure would occur once the unbalanced load exists Figure 3.b. The punching region is confined to the area near the more heavily loaded face of the column. The regions around the two adjacent sides show extensive torsion cracking, while the area near the opposite face shows little or no distress (Harris, 2004).

1.4 Review of Some British and ACI Codes on Flat Plate

1.4.1 British Standard

In British Standard BS 8110-1997 design of shear for concrete strength fcu not greater than 40 MPa should be based on:

$$v_{ck} = 0.79\sqrt[3]{100\rho}\,.\sqrt[3]{f_{cu}/25}\,.\sqrt[4]{400/d} \quad \text{.....} (1)$$

$$V_u = v_{ck}.u.d \le 1.2\sqrt{f_{cu}}\,.u.d \quad \text{.....} (2)$$

where:

v_{ck}: Ultimate shear stress in (MPa).

V_u: Ultimate shear force in (N).

$u = 4(c + 3d)$ For square loaded area in (mm).

100ρ Should not be taken as greater than 3;

$\sqrt[4]{400/d}$ Should not be taken as less than:

0.67 for members without shear reinforcement.

1 when the shear reinforcement providing a design shear resistance of 0.4 MPa.

1.4.2 ACI Code (Harris, 2004)

In ACI Code (318-05), design of slabs for two-way action should be based on:

$$V_u < \varphi V_c \quad \text{.....} (3)$$

$$V_u - w_u\,.A \quad \text{.....} (4)$$

V_c: Should be the smallest of:

$$V_c = 0.17\,(1 + \frac{2}{\beta})\sqrt{f_c'}\,b_o\,d \quad \text{.....} (5)$$

$$V_c = 0.083\,(\frac{\alpha_s\,d}{b_o} + 2\,)\sqrt{f_c'}\,b_o\,d \quad \text{.....} (6)$$

$$V_c = 0.33\,\sqrt{f_c'}\,b_o\,d \quad \text{.....} (7)$$

where:

V_u: Factored shear force at section considered in (N).

φ: Strength reduction factor (0.85)

w_u = [1.4 (dead load) + 1.7 (live load)] in (N/mm^2).

A: Shaded area in (mm^2), as in Figure 5.

b_o: Perimeter of the critical section in (mm), as in Figure 5.

$$\beta = \frac{\text{long side of column}}{\text{short side of column}}$$

α_s = 40, 30 and 20 for interior, edge and corner column respectively.

2. Objective

The present study aims are studying the cracking load, ultimate load, deflection and failure mode with its characteristics for nine specimens of flat plate slabs with different cross section properties reinforced against tension force (flexure) only.

3. Experimental Work

The experimental program consists of testing nine slabs. Three slabs S_{NN}, S_{HH} and S_{FF} are cast as one layer (uniform section) with concrete strength of 34, 48 and 21 MPa at 28 days respectively; while the other six slabs are cast with two different concrete mixes (hybrid section). So that S_{HN} consists of concrete with strength of 48 MPa in the upper half layer and 34 MPa in the lower half layer; and on the other hand S_{NH} consists of concrete with strength of 34 MPa in the upper half and 48 MPa in the lower half layer. In the hybrid section slab the compression zone may be stronger than the tension zone or verse versa. However, the uniform section slab consists of concrete with homogeneous strength and other mechanical properties in both compression and tension zone.

4. Materials Properties

4.1. Concrete

Ordinary portland cement type I complying with the Iraqi standard specification No. 5/1984 was used.

The coarse aggregate was a 12.5mm maximum size crushed gravel and the fine aggregate was natural river sand with a 2.72 fineness modulus complying with the Iraqi standard specification No. 45/1984. For high strength concrete HSC production, the water content of the mix is reduced by using a superplasticizer SP complies with ASTM C 469–86. Polypropylene fiber PPF of 0.91gm/cm^3 density, 19mm length and between 18 – 30 micron thickness was used to produce the fibrous concrete FC with 1% volume fraction. The yield strength of PPF is 350 MPa and its young modulus is in the range 5500 – 7000 MPa.

Cylinders and prisms for control tests were cast and cured with each slab in a water bath at about 25ºC for 28 days and then tested at the same time of slab testing. The mix proportions and the average results of cylinder strength f'_c and modulus of rupture f_r are given in Table 1:

4.2. Steel Bar Reinforcement

Deformed steel bars of 8mm diameter with yield stress f_y = 430 MPa, ultimate strength fu = 602 MPa and modulus of elasticity E_s = 200 GPa were used for the two directions main reinforcement of 100mm spacing c/c. as in Figure 6.a.

5. Specimen Preparation and Testing

Wooden moulds with clear dimensions of 450 x 450 x 50mm were used for casting the slab specimens, as shown in Figure 6.b. The specimens were cast as two layers of 25mm height; each layer was compacted for 2 min by vibrating table. After 28 days of curing in water bath, the specimens were dried in the laboratory temperature for one hour and then positioned in rigid steel frame to be tested as simply supported slabs with a square shape of clear dimension of 420mm, after that, applied load (steel column with square section of 40 x 40mm) and dial gauge of 0.01mm gradation were located at the slab center, as shown in Figure 6.c. Loading from MFL SYSTEM of hydraulic universal testing machine type EPP300, as shown in Figure 7, with maximum capacity of 3000 kN was applied in rate of 2 kN/min continued up to failure. Deflection was recorded in each loading stage.

6. Results of the Test

6.1 Cracking Load

From Table 2 where the cracking loads were listed, and generally having a percentage about 19 – 29% of ultimate loads, it can be clarify that for the slab S_{NN} which has a uniform section with normal strength its cracking load was 8 kN; and when compare this slab with S_{HN} which has a hybrid section with high strength concrete in the compression zone and with S_{NH} which has a hybrid section with high strength concrete in the tension zone the result is the same cracking load for all these slabs. In addition to that; by comparison among S_{FF}, S_{HF} and S_{FH} which exhibited a unique cracking load value of 6 kN the above result will enhance and lead to conclude that the cracking load value of flat plate consists of a uniform section with a specific strength will not be affected by increasing the concrete strength or using fibrous concrete in the compression or tension zone of a hybrid section flat plate. Also, the comparison among S_{FF}, S_{NN} and S_{HH} with cracking loads 6, 8 and 10 kN confirms that by increasing the section strength the appearance of cracks can be delayed.

6.2 Ultimate Load

On the side of carrying capacity, by increasing the compressive strength of the uniform section slabs S_{FF}, S_{NN} and S_{HH} from 21 to 34 and 48 MPa, as listed in Table 2, their observed ultimate loads were increased from 30 to 34 and 38 kN respectively. The SHH is stronger than S_{NN} in ultimate load by about 12%, and this behavior is expected due to increase the compressive strength of the S_{HH} section. Also, for the same reason S_{NN} is stronger than S_{FF} about 12% despite of the higher tensile strength of S_{FF} in comparison with SNN, that is to say there is no improvement for the slab ultimate load due to increasing its section tensile strength. From tacking the hybrid section slabs results on view; S_{HN} which has high strength concrete at the compression zone exhibited 6% ultimate load increase in comparison with S_{NN} but this increment stills less than 12% verified by S_{HH}. Whilst strength loss taken place with S_{NH} which has high strength concrete at the tension zone when its ultimate load reduced 18% from S_{NN}. The comparisons among S_{NN}, S_{HN} and S_{NH} revealed the activity of increasing the compression zone compressive strength in strengthening the slab and the inverse result when increasing the tension zone compressive strength. In similar manner, by appointing S_{FF}, S_{HF} and S_{FH} where the ultimate loads were 30, 32 and 26 kN respectively, the previous result will be confirmed. Thus, from the above results can be concluded that the uniform section slab enhancing will be verifiable by increasing the compression zone strength only to be hybrid section, but when selection between specific strength uniform section and hybrid section with high strength concrete at the tension zone for enhancing the slab insisting on the uniform strength section will be the unique option.

6.2 Stiffness

The observed deflection values are listed in Table 2 and the load versus deflection curves are graphed in Figure 8. For the uniform section slabs as in Figure 8.a, the stiffness of the slab increases with the section strength, therefore; S_{HH} deflection was the smallest and S_{NN} deflection was less than S_{FF} deflection. From the Figures 8.b-d which reflected the same behavior and contain comparisons among the uniform and hybrid sections, the results cleared that the stiffness of the uniform section slabs are greater than that of the hybrid section slabs even when the hybrid section has higher strength at the compression or tension zone. These responses can be showed by concentration on Figure 8.c, as example, so that S_{NN} displayed the largest stiffness and flowed by S_{FF} which is supposed as the weakest slab in the group because its compressive strength was the minimum. S_{NF} and S_{FN} produced deflections greater than S_{FF} and reflect stiffness loss in contrast with increasing their strength at compression and tension zone respectively. This result leads to the preference of using a uniform section slab with specified strength against selecting hybrid sections with increased strength at one zone in case of attempt to magnify the stiffness. On the other hand, S_{NF} showed more stiffness than S_{FN} and that means the ability of increasing the compression zone strength in reduction the deflection more than increasing the tension zone strength.

It is salutary to divide the load-deflection curves to three parts. The first part with relatively steep slope which means that the slab has high flexural stiffness, from zero loads up to first crack formation. In the second stage the smaller slope extends from cracking load to yield point to reflect stiffness reduction versus cracks development. The final part is relatively flat and exhibits little stiffness in flexure, extends from the yield point up to failures, thereby represents the ductility of slab obviously. It is clear from Figure 8 that fibrous concrete made hybrid section slab such S_{NF} and S_{FN} having flat part in their load-deflection curves despite of their non flexure failure. On the same side, the flat part of the curve is obvious in case of S_{FF} and this reflected ductility increase. This led to conclude that the use of fibrous concrete in a hybrid section slab can improve the ductility, and with uniform section slab consists of fibrous concrete the ductility can be increased.

6.3 Failure Modes

Three failure modes were noted: flexure mode represented by yield line mechanism, shear mode represented by punching shear and Flexure followed by punching shear when the section shear resistance weakened, as mentioned in Table 2 and shown in Figure 9.

In spite of deflection and cracking development with loading, there is no warning sign about failure occurrence except rapid increment of dial gage followed by the loading drop. However, the ascending increment of deflection at the last stage of loading transforms failure from brittle to ductile mode.

The observation of the uniform section slabs indicated that S_{NN} failed brittle in flexure followed by punching shear after the load drop and when the section strength increased in S_{HH} the slab failed in flexure, with 30% increasing in deflection at failure which referred to a value of ductility, and the slab was safe against punching shear, but when the section strength reduced in S_{FF} the punching shear occurred obviously with more ductility due to 70% deflection increase. The ductile action of S_{FF} may be come from its tensile strength gathered with the ductility of the polypropylene fibers. The results revealed that the shear resistance of slab is related to the section compressive strength; so that, for specific compressive strength the shear strength of the slab is weak and then the slab fails in punching shear, and when increasing the section compressive strength its shear resistance will increase but the punching shear failure stills eventual due to cracks development which cause compressive strength loss and shear resistance loss in sequence, however additional increase in compressive strength rises the shear strength and safes the slab against punching shear to be fail in flexure finally. Beside that the presence of fiber in the section improves the slab ductility and brings warranty for punching shear failure which is brittle failure in case of conventional concrete slab.

From concentration on the hybrid section slabs, the clear result is the effective action which is by increasing the compression zone strength the failure mode can be transformed from punching shear to flexure, thus SFF failed by punching shear and S_{NF} failed in flexure followed by punching shear, and in the corresponding case S_{NN} failed in flexure followed by punching shear and S_{HN} failed in flexure.

The comparisons between S_{HH} and S_{HN} which failed in flexure and between S_{NN} and S_{NF} which failed in flexure followed by punching shear revealed the ability of the hybrid section slab on preserving the failure mode of a uniform section slab with a certain strength when this strength is equal to the compression zone strength of the hybrid section.

On the wise of increasing the tension zone strength of the hybrid section slab, the failure mode will not improve, this is clear from S_{NN} and S_{NH} which failed in flexure followed by punching shear and confirmed with S_{FF} and S_{FN} which failed by punching shear.

6.4 Punching Shear Failure Zone

It is observed that in plan the shape of the punching failure zone is approximately square which is similar to the loading column, as shown in Figure 9 and the measured failure zone perimeters are listed in Table 2.

From the uniform section slabs S_{NN} and S_{FF} and their failure zones perimeters 1060 and 920mm respectively can be noted that; with increasing the section strength the failure zone perimeters can be magnified. By increasing the compression zone strength in hybrid section slab the failure zone perimeter will decrease as observed through S_{FF}, S_{NF} and S_{HF} where the perimeters were 920, 600 and 580mm respectively. While by increasing the tension zone strength in hybrid section slab the failure zone perimeter will increase as observed in S_{FF}, S_{FN} and S_{FH} where the perimeters were 920, 1060 and 1100mm respectively, and also, the result is the same in S_{NN} and S_{NH} when their failure perimeters were 1060 and 1080mm respectively even which are approximately equal.

The conclusion which can be drawn from these results is the influence of failure zone perimeter by the position of the more strength concrete in the slab section.

6.5 Punching Shear Failure Angle

The measured failure zones angles are listed in Table 2 and their values for almost slabs were less than 30°. It is observed that there is a geometrical correlation between the punching failure zone and angle due to the truncated cone cracking leads to decrease the failure angle when the punching zone increases and verse versa.

For S_{FF} the failure angle was 27.76° and when the section strength increased in S_{NN} the punching failure zone increased and its angle decreased to 23.96°. In hybrid section slabs; the failure angle obeyed the more strength concrete position; thereby, increasing the compression zone strength the angle increases and by strengthening the tension zone this angle decreases, that is clear from S_{HF} and S_{FH} where their failure angles were 33.60° and 23.05° respectively.

7. Conclusions

1. The uniform section is more suitable than the hybrid section for improving the structural behavior of flat plate systems. By strengthening the uniform section more improving for the slab can be gained.
2. The upper layer of the flat plate which defined as the compression zone has the dominator on slab behavior; therefore, this layer must be intended in strengthening and improving the slab behavior.
3. There is no avail from increasing the tension zone strength of the hybrid section slab for improving

the ultimate strength, stiffness, mode of failure or failure zone characteristics; but in contrast the ductility of the structure will improve.

4. The ultimate strength increase which can be achieved by increasing uniform section slab strength is about twice a corresponding increase can be gained from hybrid section strength slab by increasing its compression zone strength only.
5. By increasing the strength of the uniform section or at least the compression zone in hybrid section one, the failure mode can be transformed from punching shear in brittle manner to flexure mode with increasing of about 70% in ductility.
6. In the uniform section slabs the punching shear zones are greater than that zones in the corresponding hybrid section slabs and punching shear angles are less than that angles in the hybrid sections, and in all cases failure zone are not less than 13 times the column area and failure angle are about 30°.

Notations

b_o: perimeter of the critical section indicating punching shear failure zone.

E_c, Es: modulus of elasticity of concrete and reinforcement steel.

FC: fibrous concrete with 1% volume fraction and compressive strength of 21 MPa.

f'_c, f_r: compressive and flexural strength of concrete.

f_y, fu: yield stress and ultimate strength of reinforcement steel.

P_{cr}, P_u: cracking and ultimate load respectively.

HSC: high strength concrete with compressive strength of 48 MPa.

NSC: normal strength concrete with compressive strength of 34 MPa.

PPF: polypropylene fiber used for fibrous concrete production.

SP: superplasticizer used for high strength concrete production.

S_{NN}: uniform slab with normal strength concrete for all the section.

S_{NH}: hybrid slab with normal concrete at top layer and high strength concrete at bottom one.

S_{HN}: hybrid slab with high strength concrete at top layer and at normal concrete bottom one.

S_{HH}: uniform slab with high strength concrete for all the section.

S_{NF}: hybrid slab with normal concrete at top layer and fibrous concrete at bottom one.

S_{FN}: hybrid slab with fibrous concrete at top layer and at normal concrete bottom one.

S_{FF}: uniform slab with fibrous concrete for all the section.

S_{FH}: hybrid slab with fibrous concrete at top layer and high strength concrete at bottom one.

S_{HF}: hybrid slab with high strength concrete at top layer and at fibrous concrete bottom one.

Greek letters

Δ_u: deflection at ultimate load.

θ: punching shear failure angle.

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Table (1) Mix Proportions and Mechanical Properties of Concrete

Group	Mix Proportions kg/m^3						Slump mm	Mechanical Properties MPa		
	Cement	Sand	Gravel	Water	SP	PPF		f'_c	f_r	† f_r
NSC	420	600	1200	180	–	–	100	34	4.8	4.1
HSC	420	600	1200	120	6.3	–	100	48	7.8	4.8
FC	420	600	1200	200	–	9.1	80	21	6.2	3.2

† $f_r = 0.7\sqrt{f'c}$

Table (2) Strength and Deformation of the Tested Slabs

Beam Symbol	P_{cr} kN	P_u kN	Δ_u mm	b_o mm	θ deg.	Mode of Failure
† S_{NN}	8	34	5.73	1060	23.96	**Flexure followed by punching**
S_{NH}	8	28	5.02	1080	23.50	**Flexure followed by punching**
S_{HN}	8	36	7.22	-	-	**Flexure**
S_{HH}	10	38	7.59	-	-	**Flexure**
S_{NF}	6	24	7.00	600	32.27	**Flexure followed by punching**
S_{FN}	4	18	6.46	1060	23.96	**Punching shear**
S_{FF}	6	30	7.33	920	27.76	**Punching shear**
S_{FH}	6	26	6.42	1100	23.05	**Punching shear**
S_{HF}	6	32	6.96	580	33.60	**Flexure followed by punching**

† Reference Slab

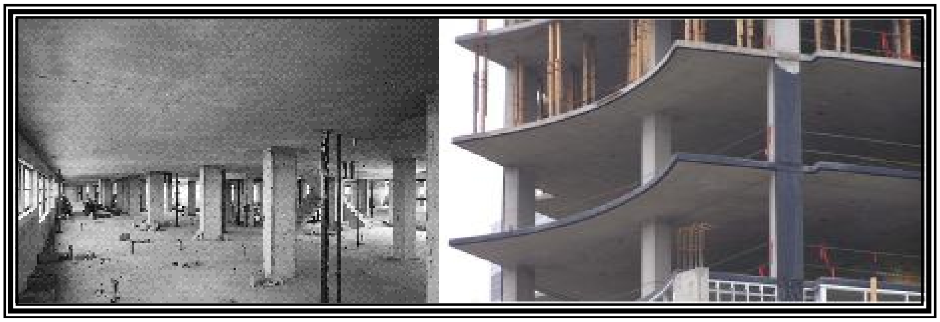


Figure (1) Flat Plate Constructions (Nilson, 2004)

Figure (2) Punching Shear Failure in Flat Plate Constructions (Langohr, 1976)

a. Failing in Flexure b. Flexural Punching Shear

Figure (3) Tensile Face (Top Surface) of Typical Flat Plate Slab (Harris, 1997)

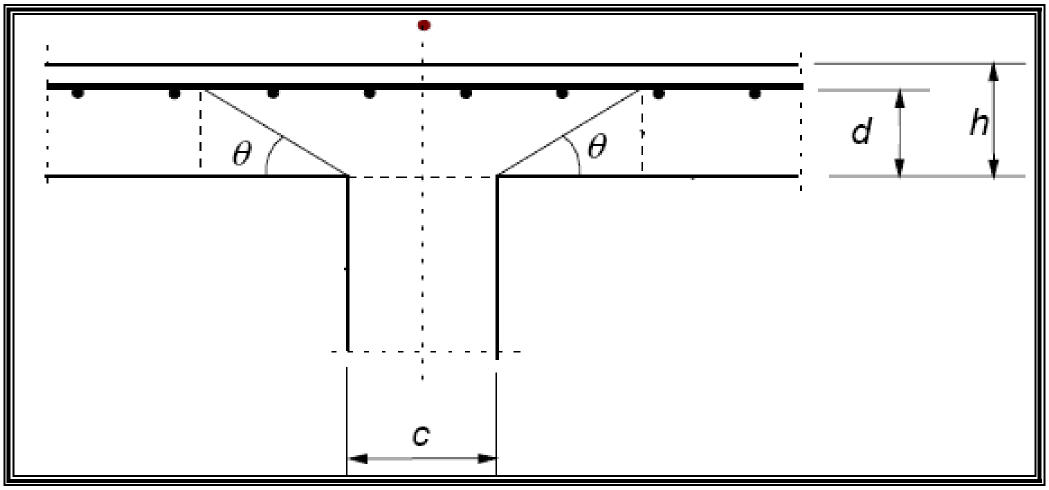


Figure (4) Punching Shear Failure Diagram

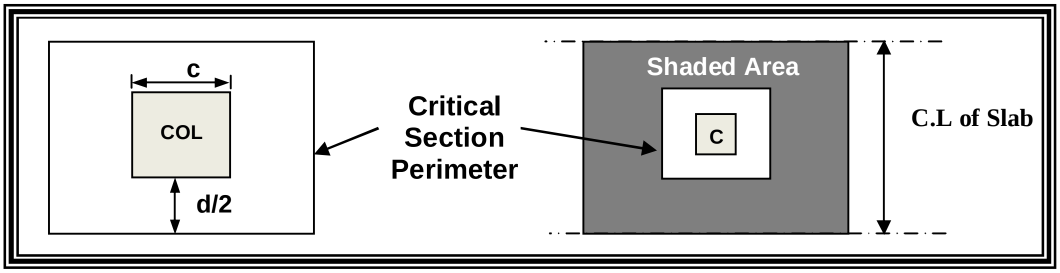
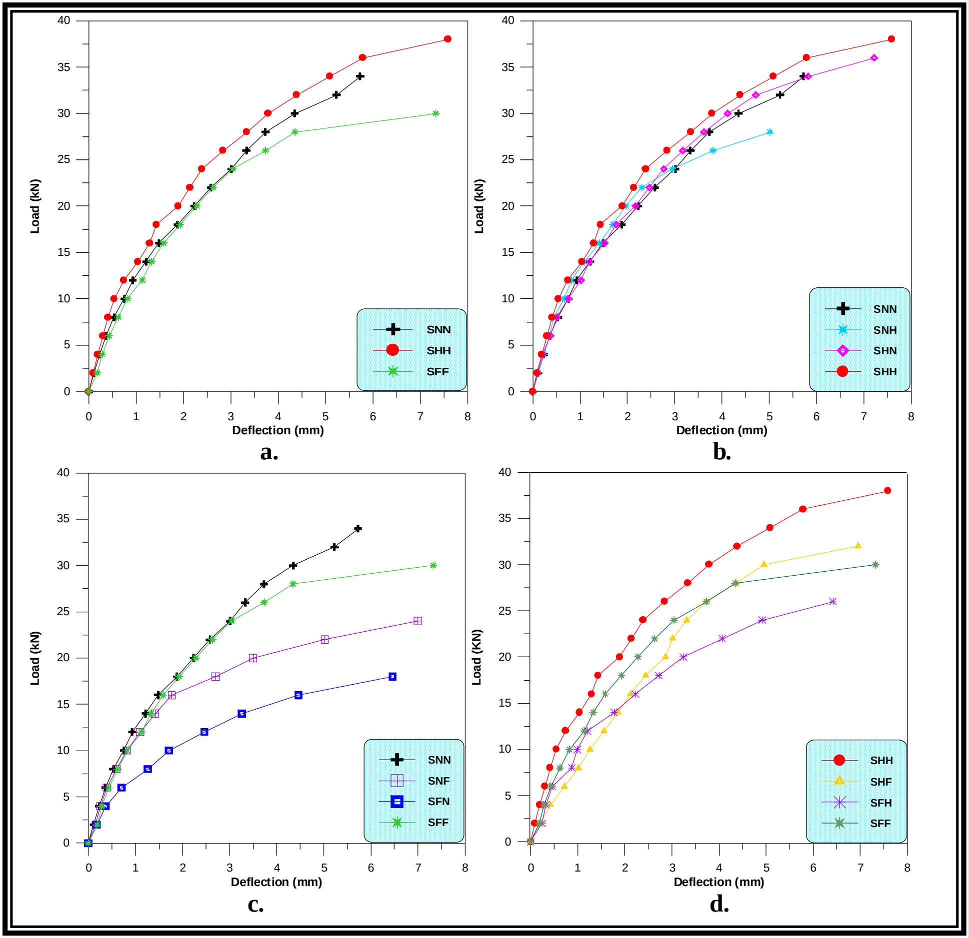


Figure (5) Critical Section for Punching Shear and Area of Shear Force (ACI Code (318-05), 2005)

a. Steel Bars b. Mould c. Test Preparation

Figure (6) Specimen Preparation

Figure (7) Testing Machine

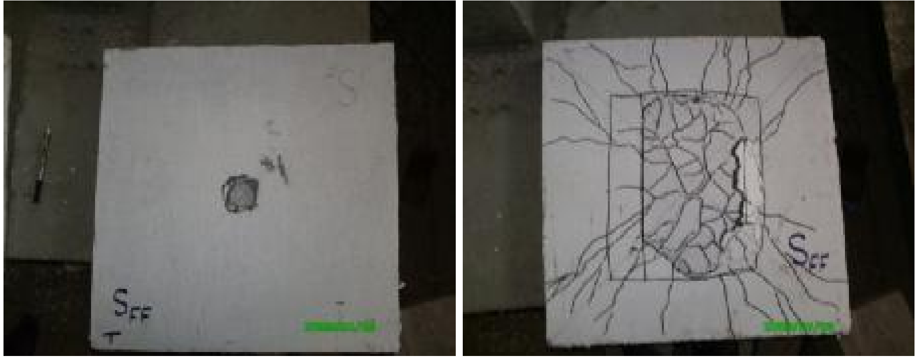


a.
b.
c.
d.

Figure (8) Load-Deflection Curves

a. Flexure Mode of Failure

b. Flexure Followed by Punching Shear Mode of Failure



c. Punching Shear Mode of Failure

Figure (9) Cracking and Failure Modes of the Tested Slabs