Punching Shear Behavior of Fibrous Self –Compacting Concrete Flat Slabs

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Received on: 23/3/2014 & Accepted on: 30/9/2014

ABSTRACT

This research is devoted to study the mechanical properties of fibrous self-compacting concrete (FSCC) as materials as well as studying the punching shear behavior of FSCC slabs. The experimental program includes investigating the effect of steel fiber volumetric ratio (V_f) and absence of limestone powder on some important mechanical properties of FSCC such as compressive strength, modulus of elasticity, splitting tensile strength and modulus of rupture. Additional experimental tests are also conducted to study the effect of V_f, steel reinforcement ratio (ρ) and slab thickness on the punching shear behavior (in terms of load-deflection response and ultimate failure load),and the failure characteristics of the punching shear (in terms of observation of failure, shape of the failure zone, size of the failure zone, failure angles, critical section perimeters and ultimate punching shear stress) of simply supported reinforced FSCC slabs having dimensions of 1000×1000× 50 or 70 mm under concentrated load at the center of the slab.

Keywords: Punching shear + self-compacting concrete+ flat slab+ fiber concret

سلوك القص الثاقب لبلاطات الخرسانة ذاتية الرص والمسلحة بالالياف

الخلاصة

يهتم البحث الحالي بدراسة الخواص الميكانيكية للخرسانةذاتية الرص والمسلحة بالالياف(FSCC) كمادة إضافة إلى دراسة تصرف القص الثاقب (Punching Shear) للبلاطات المصنعة من هذه الخرسانة. يتركز البرنامج العملي من البحث على دراسة واستقصاء تأثير النسبة الحجمية للألياف الفولاذية وانعدام مسحوق الغبرة على بعض الخواص الميكانيكية المهمة لخلطة الخرسانة ذاتية الرص والمسلحة بالألياف مثل مقاومة الانضغاط للخرسانة ومقاومة شد الانشطار ومعامل المرونة ومعامل الانثناء. يتضمن البحث أيضا دراسة تأثير نسبة حديد التسليح وسمك البلاطات إضافة إلى المتغيرات أعلاه على تصرف القص الثاقب (بدلالة منحنى الحمل-الهطول,حمل الفشل الأقصى,خصائص الفشل وانتشار التشققات) للبلاطات إضافة إلى خصائص الفشل للقص الثاقب (بدلالة مساحة الفشل, زاوية الفشل, محيط المنطقة الحرجة والانفعال الأقصى للقص الثاقب) لبلاطات مصنعة من الخرسانةذاتية الرص والمسلحة بالالياف بأبعاد(X1000X 501000 أو 70) ملم ذات إسناد بسيط تحت تأثير حمل مركز في منتصف البلاطة.

https://doi.org/10.30684/etj.32.12A.3
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INTRODUCTION

Reinforced concrete slabs may be carried directly by the columns without using beams, drop panels or columns capitals. Such slabs are described as "flat plates". This type of structures has more space in addition to its pleasant appearance. Flat plates have been widely used due to the reduced construction cost. They are also economical in their formwork and lead to simpler arrangement of flexural, reinforcement. An additional advantage of a flat plate is reduced building storey heights that result in more usable space in buildings for a given or limited height. Many other advantages can be achieved by flat plates, such as a reduction in dead loads on the columns and foundations [1].

One of the major problems in such structures is the punching shear failure (also known as two-way action shear) that takes place when a plug of concrete is pushed out from the slab immediately above the columns. The pushed plug takes the form of a frustum cone or a cutoff pyramid with a minimum cross section at least as large as the loaded area[2]. Punching shear failure of slabs is usually sudden and leads to progressive failure of flat plate structures; therefore, caution is needed in the design of slabs and attention should be given to avoid the sudden failure condition.

Self-Compacting Concrete (SCC)

Usually, slabs have small thickness and contain congested reinforcement. Therefore, the conventional concrete does not flow well when it travels to the bottom and does not completely fill the bottom part. This results in many problems in concrete such as, voids, segregation, weak bond with reinforcement bars and holes in its surface. Therefore, the self-compacting concrete (SCC) is very appropriate type for casting these members.

Self-compacting concrete, provides distinct advantages over conventional vibrated concrete due to liquid nature such as: elimination of above mentioned problems, low noise level in construction, faster construction and improving quality and durability, no need to vibration where it is able to fill all spaces in the formwork and passes through reinforcing bars by its own weight[3,4].

The difference in some properties between the conventional vibrated concrete and the self-compacting concrete requires necessity to investigate the behavior and capacity of structural members constructed using this type of concrete. Therefore, the behavior of slabs made using SCC is experimentally investigated in this research work. Because of the lesser amount and smaller maximum size of coarse aggregate used in SCC compared with conventional vibrated concrete, one can expect that the shear strength of slabs made by SCC is lesser than that carried out by slabs made using conventional vibrated concrete, where the interlock mechanism of coarse aggregate is weaker which represents an important part of the total shear strength parts for these members. But the well self-compaction and regularity of microstructure of this type of concrete reduce the weaken positions in it and may lead to an increase in its efficiency to resist the shear stresses.

This liquid property in SCC makes it appropriate to use steel fibers in its mix to improve its mechanical properties, where using them in SCC is easier than using it in conventional vibrated concrete [5]. Therefore, the use of steel fibers is one of the important parameters considered in this study. Because of weaker interlock mechanism of coarse aggregate in SCC, the steel fibers may have more prominent role in improving the shear strength of SCC slabs compared with those made using conventional vibrated concrete.

Experimental Program

In the experimental work, control specimens were cast which were three cylinders and four cubes for compression test, one cylinder for modulus of elasticity, three cylinders for splitting strength and three prisms for modulus of rupture for each mix. Details of these control specimens are shown in Table (1).

Table (1) Specifications of the control specimens

Type of test	Number and type of specimens	Specimens dimension mm
Compression	3 cylinders	100X200
	4 cubes	100X100
Compression stress strain	1 cylinder	150X300
Splitting tensile strength	3 cylinders	100X200
Modulus of rupture	3 prisms	100X100X500

Four variables are investigated in this study to show their effects on the punching shear strength of the FSCC slabs. These variables are:
1. Percentage of steel fibers.
2. Flexural steel reinforcement ratio.
3. Thickness of the slab.
4. Type of concrete [conventional concrete (CC)&FSCC].

Table (2) illustrates the details of all the test slabs.

Materials:

Cement:

Ordinary Portland cement (type I) of Tasluja Factory is used in the present study. Test results of chemical composition and physical properties of the used cement tested by National Center for Construction Laboratories and Researches in Baghdad comply with the requirements of I.Q.S. No.5, 1984[6].

Fine Aggregate

Al-Ukhaider natural sand is used in concrete mix. Before using it, the sieve analysis is performed at Material Laboratory in Engineering College of Al-Mustansiriya University to ensure its validity for mixing. The fineness modulus, depending on this analysis, is 2.78. The sieve analysis results of the sand comply with the limits of the Iraqi Specification No.45/1984[7].

Coarse Aggregate (Gravel)

Crushed gravel of maximum size 10 mm brought from Al-Niba'ee region is used. Before using it, the sieve analysis is performed at Material Laboratory in Engineering College of Al- Mustansiriya University to ensure its validity for mixing and choosing the primary proportions of mix materials. The grading of this aggregate conforms to the Iraqi specification No.45/1984[7].

Limestone Powder

Limestone powder is locally named “Al-Gubra” brought from Al-Mousel district and has been used as filler for concrete production for many years. The particle size of the limestone powder is less than 0.125 mm, which satisfies EFNARC 2002[8] recommendations

Superplasticizer

In this work, the super plasticizer used is known commercially as "GLENIUM51". It is a new generation of modified polycarboxylic ether. It is compatible with all Portland cements that meet recognized international standards. Super plasticized concrete exhibits a large increase in slump without segregation. However, this provides enough period after mixing for casting and finishing the concrete surface.

Steel Reinforcement

Two sizes of deformed steel bars of nominal diameter 4 and 6 mm were used as slab reinforcement. Two reinforcement ratios (ρ) are used in each group of the tested slabs. The tension tests of all these bars gave the properties listed in Table (3). The results of testing these bars met **ASTM A615**[9] requirements for Grade 60 steel.

Bar size and spacing between bars are shown in Table(4) for each slab specimen which was taken to be identical in both directions.

Table (2) Details of all the test slabs of the present investigation

Group No.	Slab Designation	Flexural steel reinforcement	Steel reinforcement ratio (ρ)	Steel fibers % by volume	Slab thickness (mm)
Group One (Normal concrete slabs as reference slabs) (CC)	S1	Ø 4mm @ 100mm c/c	0.0033	0	50
	S2	Ø 6mm @ 150mm c/c	0.0033	0	70
	S3	Ø 4mm @ 50mm c/c	0.0066	0	50
	S4	Ø 6mm @ 75mm c/c	0.0066	0	70
Group Two (FSCC0)	S5	Ø 4mm @ 50mm c/c	0.0066	0	50
	S6	Ø 4mm @ 100mm c/c	0.0033	0	50
	S7	Ø 6mm @ 75mm c/c	0.0066	0	70
	S8	Ø 6mm @ 150mm c/c	0.0033	0	70
Group Three (FSCC1)	S9	Ø 6mm @ 150mm c/c	0.0033	1	70
	S10	Ø 6mm @ 75mm c/c	0.0066	1	70
	S11	Ø 4mm @ 50mm c/c	0.0066	1	50
	S12	Ø 4mm @ 100mm c/c	0.0033	1	50
Group Four (FSCC2)	S13	Ø 6mm @ 75mm c/c	0.0066	2	70
	S14	Ø 4mm @ 50mm c/c	0.0066	2	50
	S15	Ø 4mm @ 100mm c/c	0.0033	2	50
	S16	Ø 6mm @ 150mm c/c	0.0033	2	70

Table (3) Properties of the steel bars in tension*

Nominal diameter mm	Actual diameter mm	Weight (kg/m)	Yield stress MPa	Yield strain mm/mm	Ultimate strength MPa	Ultimate strain mm/mm
4	4.22	0.11	395	0.0018	485	0.143
6	5.92	0.216	435	0.0023	535	0.165

*Carried out at the College of Engineering, Al-Mustansiriya University

Table (4) Steel reinforcement details of the tested slabs

Steel Ratio (%)	Bar Nominal Diameter (mm)	Thickness of Reinforced Concrete Slab (mm)	Bar Spacing in each Direction (mm)
0.33	4	50	100
	6	70	150
0.66	4	50	50
	6	70	75

Hooked Steel Fibers (HSF)

Hooked short steel fibers were used throughout the experimental program. This type of steel fibers was manufactured by the SPI Fiberforce Company, Turkey. The properties of the used steel fibers are presented in Table (5).

Table (5) Properties of the used steel fibers*

Property	Specifications
Relative Density	**7860 kg/m^3**
Ultimate strength	**2000 MPa**
Modulus of Elasticity	**$200x10^3$MPa**
Strain at proportion limit	**5650 $x10^{-6}$**
Poisson's ratio	**0.28**
Average length	**30 mm**
Nominal diameter	**0.375 mm**
Aspect ratio (L_f/D_f)	**80**

*According to the certificate of conformity

Concrete Mix Proportions

To determine mix proportions for different types of concrete adopted in this study, the tables of mix proportion suggested by Al-jadiri[10] in her research carried out in 2008 is adopted with some modifications after performing many trial mixes. Table (6) gives the final quantities by weight of materials used in preparation of self-compacting concrete per cubic meter for the different mixes adopted in this work.

Table (6) Proportions of FSCC mixes per cubic meter

Mix name	Cement (kg)	Limestone powder (LSP) (kg)	Water (liter)	Sand (kg)	Gravel (kg)	Super plasticizer (liter)	Steel fibers Kg (V_f %)
CC	400	---	180	600	1200	---	---
NSCC0	400	170	190	797	767	7.5	0(0)
NSCC-1	400	170	190	797	767	8.5	78.5(1)
NSCC-2	400	170	190	797	767	10	157(2)

Mixing

The procedure of mixing is stated as follows:

1.The fine aggregate is added to the mixer with 1/3 quantity of water and mixed for 1 minute.

2.The cement and limestone powder are added with another 1/3 quantity of water. Then, the mixture is mixed for 1 minute.

3.The coarse aggregate is added with the last 1/3 quantity of water and 1/3 dosage of super plasticizer, and the mixing time lasts for 1½ minutes then the mixer is left for 1/2 minute to rest.

4.Then, the 2/3 of the leftover of the dosage of super plasticizer is added and mixed for 1½ minutes.

5.The concrete is then discharged for performing fresh properties and casting.

6.However, for mixes containing steel fibers, the fibers are added during step 4 and mixed for 2 minutes to achieve homogenous distribution of fibers.

Tests on Fresh Self Compacting Concrete

In this work, consideration of concrete mix as a self-compacting concrete is verified by three standard tests: Slump flow, T_{50cm} slump flow and L-box as shown in Figures (1) and (2)

Figure (1) Spreading concrete in Slump Flow test of SCC

Figure (2) Flowing of concrete in horizontal section in L-box test of SCC

Fresh FSCC Properties Results

Table (7) illustrates the results of these three tests that carried out on SCC mixes and the comparisons with the standard limitations are also presented. From this table, one can notice that the results of all mixes tests satisfy the requirements of EFNARC[8] specifications. The deviation is acceptable according ACI-237R-07[11] which gives limitation of 450-760 mm for slump flow test and according to Advanced Concrete Masonry Center[10] which suggests a value of >600 mm for slump flow and a value of < 7 sec for T_{50} slump flow test for mixes which are designed with characteristic cube strength not less than 60 MPa

Table (7) Tests results of fresh properties for SCC

Mix name	Slump flow (mm)	T_{50} (sec)	L – box (H_2/H_1)
NSCC	770	2.5	1
NSCC-1	700	4	0.90
NSCC-2	640	5	0.81
Limits of EFNARC[8]	650-800	2-5	0.8-1

Hardened SCC Mechanical Properties Results

Table (8) shows test results of mechanical properties obtained for the two mixes (CC& NSCC). These properties are concrete compressive strength (f'_c), splitting tensile strength (f_t), modulus of rupture (f_r) and modulus of elasticity (E_c). Each value presented in this table represents the average value of three specimens.

Table (8) Tests results of mechanical properties for hardened CC & SCC

Mix name	f'_c (MPa)	f_{cu} (MPa)	f_t (MPa)	f_r (MPa)	E_c(MPa)
CC	**30.59**	**36.1**	**3.08**	**4.25**	**24341**
NSCC	**32.84**	**40.75**	**3.12**	**4.41**	**24897**
NSCC-1	**34.54**	**41.9**	**4.15**	**7.02**	**26184**
NSCC-2	**39.44**	**46.3**	**4.56**	**7.80**	**36287**

Slab Punching Shear Test Results

Load-Deflection Characteristics

In this study, 20slabs were tested. These slabs are identical in size, different in concrete type (C.C. and FSCCC), fiber volume fraction, flexural steel reinforcement ratio and slab thickness. According to these variables ultimate loads, crack patterns, critical sections, angles of failure as well as modes of failure are different from one another. So, these slabs are divided into five groups. All results are shown in Tables (9), (10), (11) and (12).

Table (9) Load - Deflection Characteristics of Group 1(CC)

Slab NO.	Thickness (mm)	ρ	Steel fiber% by vol.	$f'c$ (MPa)	First crack load (F.C.L) (kN)	Ultimate load (U.L) (kN)	Midspan deflection at first crack (mm)	Midspan deflection at ultimate load (mm)	Mode of failure
S1	50	0.0033	0	30.95	9.5	52.5	0.38	5.78	Punching+ flexure
S2	70	0.0033	0		11.5	67.5	0.23	7.22	Punching+ flexure
S3	50	0.0066	0		12.5	57.5	0.45	4.4	Punching
S4	70	0.0066	0		26	108	0.28	6.17	Punching

Table (10) Load - Deflection Characteristics of Group2 (FSCC0)

Slab NO.	Thickness (mm)	ρ	Steel fiber % by vol.	f´c (MPa)	First crack load (F.C.L) (kN)	Ultimate load (U.L) (kN)	Midspan deflection at first crack (mm)	Midspan deflection at ultimate load (mm)	Mode of failure
S6	50	0.0033	0	32.84	10	58.5	0.15	6.8	Punching+ flexure
S8	70	0.0033	0		12	78	0.18	8.88	Punching+ flexure
S5	50	0.0066	0		13	65	0.46	5.15	Punching
S7	70	0.0066	0		26.5	124	0.24	7.95	Punching

Table (11) Load - Deflection Characteristics of Group3 (FSCC1)

Slab NO.	Thickness (mm)	ρ	Steel fiber % by vol.	f´c (MPa)	First crack load (F.C.L) (kN)	Ultimate load (U.L) (kN)	Midspan deflection at first crack (mm)	Midspan deflection at ultimate load (mm)	Mode of failure
S12	50	0.0033	1	34.54	12.5	76	0.6	8.04	Punching+ flexure
S9	70	0.0033	1		15	95	0.43	10.3	Punching
S11	50	0.0066	1		15.5	84	0.85	6.78	Punching
S10	70	0.0066	1		30.5	148	0.6	9.15	Punching

Table (12) Load - Deflection Characteristics of Group4 (FSCC2)

Slab NO.	Thickness (mm)	ρ	Steel fiber % by vol.	f´c (MPa)	First crack load (F.C.L) (kN)	Ultimate load (U.L) (kN)	Midspan deflection at first crack (mm)	Midspan deflection at ultimate load (mm)	Mode of failure
S15	50	0.0033	2	39.44	15	92	0.54	9.98	Punching
S16	70	0.0033	2		17	128	0.34	13.09	Punching
S14	50	0.0066	2		18.5	102	0.8	8.79	Punching
S13	70	0.0066	2		37.5	182	0.63	11.09	Punching

Ultimate Failure load

The use of fibers self-compacting concrete in slabs leads to significant increases in ultimate failure load. Tables (13) to (16) show the percentage increases for slabs with (50 and 70mm) thicknesses and (0.0033 and 0.0066)flexural steel reinforcement ratio, respectively. From these tables one can see that the improvement in compressive strength has far exceeded the results achieved with conventional concretes. This resulted in an increase in the punching shear strength of the reinforced FSCC slabs by about (11.43-89.63)% above that of the reference slab.

Such results indicate that both the shear and flexural strengths of the FSCC slabs are increased substantially with the use of steel fibers and increased fiber content. The orientation of fibers across the initiating cracks restricted their propagation and transmitted the tensile stresses uniformly to the concrete media surrounding the crack instead of being concentrated at its tip. This would result in a reduced stress intensity at the crack tip so that an additional load could be accommodated by the slab before the initiating cracks transformed into the whole section.

Table (13) Ultimate failure load for slabs with (H=50mm& ρ=0.0033)

Slab No.	Concrete type	Slab Thickness	ρ	$f'c$ (MPa)	Pu (kN)	Increasing ratio% (Pu)	P_{cr} (KN)	Increasing ratio% (P_{cr})
S1	C.C.	50	0.0033	30.95	52.5	0	9.5	0
S6	FSCC0	50	0.0033	32.84	58.5	11.43	10	5.3
S12	FSCC1	50	0.0033	34.54	76	44.45	12.5	31.6
S15	FSCC2	50	0.0033	39.44	92	75.24	15	57.9

Table (14) Ultimate failure load for slabs with (H=70mm& ρ=0.0033)

Slab No.	Concrete type	Slab Thickness	ρ	$f'c$ (MPa)	Pu (kN)	Increasing ratio% (Pu)	P_{cr} (KN)	Increasing ratio% (P_{cr})
S2	C.C.	70	0.0033	30.95	67.5	0	11.5	0
S8	FSCC0	70	0.0033	32.84	78	15.55	12	4.3
S9	FSCC1	70	0.0033	34.54	95	40.47	15	30.4
S16	FSCC2	70	0.0033	39.44	128	89.63	17	47.8

Table (15) Ultimate failure load for slabs with (H=50mm& ρ=0.0066)

Slab No.	Concrete type	Slab Thickness	ρ	$f'c$ (MPa)	Pu (kN)	Increasing ratio% (P_u)	P_{cr} (KN)	Increasing ratio% (P_{cr})
S3	C.C.	50	0.0066	30.95	57.5	0	12.5	0
S5	FSCC0	50	0.0066	32.84	65	13.04	13	4
S11	FSCC1	50	0.0066	34.54	84	46.08	15.5	24
S14	FSCC2	50	0.0066	39.44	102	77.39	18.5	48

Table (16) Ultimate failure load for slabs with (H=70mm& ρ=0.0066)

Slab No.	Concrete type	Slab Thickness	ρ	$f'c$ (MPa)	Pu (kN)	Increasing ratio% (Pu)	P_{cr} (KN)	Increasing ratio% (P_{cr})
S4	C.C.	70	0.0066	30.95	108	0	26	0
S7	FSCC0	70	0.0066	32.84	124	14.81	26.5	1.9
S10	FSCC1	70	0.0066	34.54	148	37.03	30.5	17.3
S13	FSCC2	70	0.0066	39.44	182	66.66	37.5	44.2

Failure Characteristics

Observation of Failure

Punching shear failure had occurred suddenly in all the tested slabs without steel fibers. There is no sign of warning before the occurrence of failure, except the rapid movement of dial gage.

The failure of the reference slabs and FSCC slabs without steel fibers was sudden and very brittle as compared to those with steel fibers in which failure was in a gradual manner.

In the case of sudden failure, the dial gage faced a sudden shock and moved from its position in some slabs and a plug of concrete is pushed out from the slab immediately, especially those slabs of group 1&2. In the others, the dial gage recorded fast movement

before failure. The overall cracking behaviors of some of the tested slabs are shown in Figures (3).

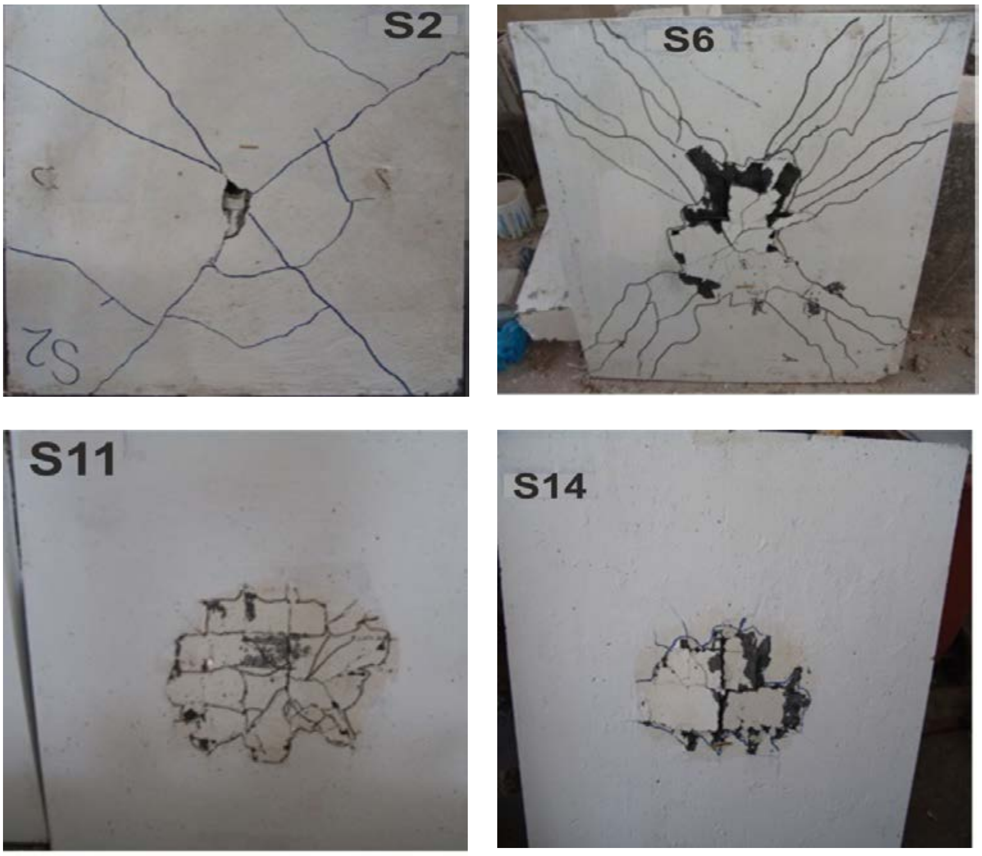

Figure (3): Cracks pattern

Shape of the Failure Zone

It was observed that the shape of the failure zone in plane is ranging from a circle to a square with round corners. The shapes can be modeled similar to that proposed by the **ACI 318M-11**[12]

Size of the Failure Zone and Failure Angles

The punching failure mode was typically in the shape of pyramid making an angle Ø with the bottom face of the slab. The failure angles and the failure punching zone of the punching pyramid were measured by indicating the dimensions of the crushed zone at the center line passing through the loaded area. It was observed that the angle of failure was about 17.5° for reference slabs. The angle was gradually decreased to about 15° for FSCCC without steel fibers, also the angle was increased to 18.5° and 20° for FSCCC (with 1% steel fibers), FSCCC(with 2% steel fibers) respectively.
Although the failure angle was more in slabs with steel fibers, the failure pyramid that was pushed out in slabs without steel fibers has a much wider base than that in slabs with steel fibers as shown in the figures of crack patterns. This indicates that steel fibers help to prevent the disintegration of concrete cover under the flexural steel reinforcement, and tend to integrate the hole section. Figures (4) to (7) and Table (17) show the value of the punching failure angle Ø for all tested slabs. Table (17) also includes the area of the failure punching zone calculated after measuring the dimensions of the crushed zone at the center line passing through the loaded area.

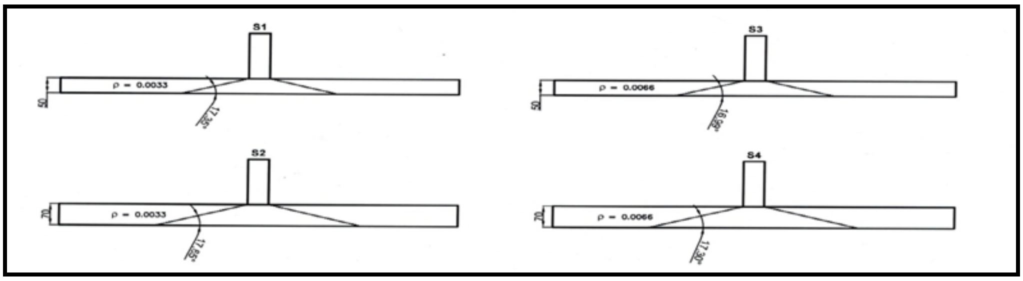

Figure (4) angle of failure of slabs of group 1 (C.C.)

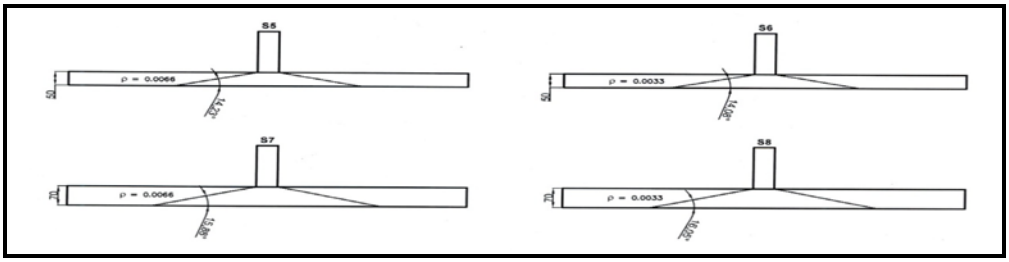

Figure (5) angle of failure of slabs of group 2 (FSCC0)

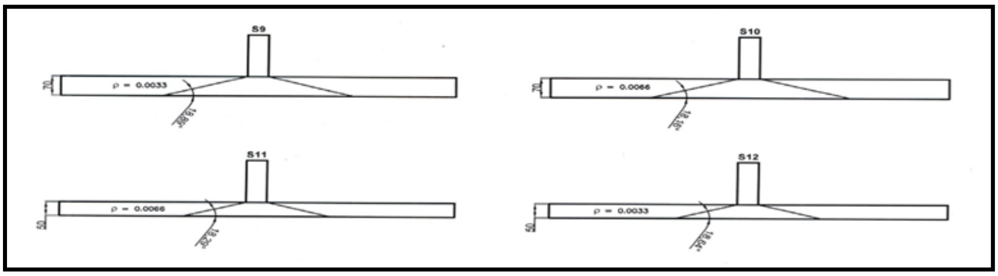

Figure (6) angle of failure of slabs of group 3 (FSCC1)

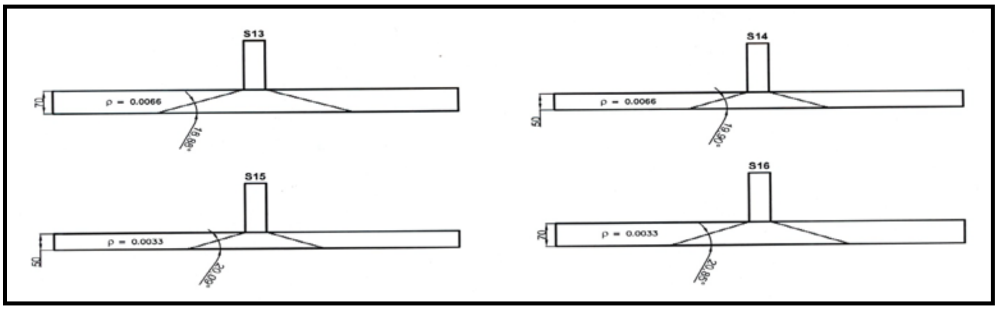

Figure (7) angle of failure of slabs of group 4 (FSCC2)

Table (17) Failure area and angle of failure of the tested slabs

Slab NO.	Type Of concrete	$f'c$ (MPa)	Steel fiber% by vol.	Thickness (mm)	Steel reinforcement ratio (ρ)	Measured Failure Area (mm^2)	Failure Angle Ø°
S1	C.C.	30.95	0	50	0.0033	89207	17.35
S2	C.C.		0	70	0.0033	211004	17.65
S3	C.C.		0	50	0.0066	101603	16.99
S4	C.C.		0	70	0.0066	244029	17.3
S5	FSCC	32.84	0	50	0.0066	124651	14.23
S6	FSCC		0	50	0.0033	108869	14.08
S7	FSCC		0	70	0.0066	267211	15.88
S8	FSCC		0	70	0.0033	230874	16.05
S9	FSCC	34.54	1	70	0.0033	198829	18.89
S10	FSCC		1	70	0.0066	220789	18.16
S11	FSCC		1	50	0.0066	92102	18.29
S12	FSCC		1	50	0.0033	78989	18.64
S13	FSCC	39.44	2	70	0.0066	199205	18.88
S14	FSCC		2	50	0.0066	80798	19.9
S15	FSCC		2	50	0.0033	67205	20.09
S16	FSCC		2	70	0.0033	172211	20.85

Previous tests elsewhere[13] had shown that the angle of failure was about 19° for slabs without steel fibers and gradually increased to 24° in slabs with 1% crimped steel fibers content.

The present test shows also a similar trend in principle that the size of failure zone decreased by addition of steel fibers in slabs of group 3,4 and 5.

Critical Section Perimeters

The distance of the critical section for the slabs tested in this investigation is considered as half the distance between the end of the failure surface and the face of

the column. The calculated distances are based on the measured area. Figure (8) shows the method used to calculate the critical sections for the tested slabs.
In **ACI 318M-11[12]** and **BS8110[14]** codes, the critical punching shear section is assumed to be located at distance d/2 and 1.5d from the column face, respectively (where d is the effective depth of the slab). **Tuan[15]** showed that the critical section perimeters equal to(2d) for high strength concrete and this conformed with **CEB-**FIPMC-90[16].

Previous research[13] showed that the critical section perimeter ranged from 1.16h to 1.5h for slabs without steel fibers and 1.06h to 1.25h for slabs with steel fibers.
Table (18) lists the calculated distances and the critical section for each group of the tested slabs.

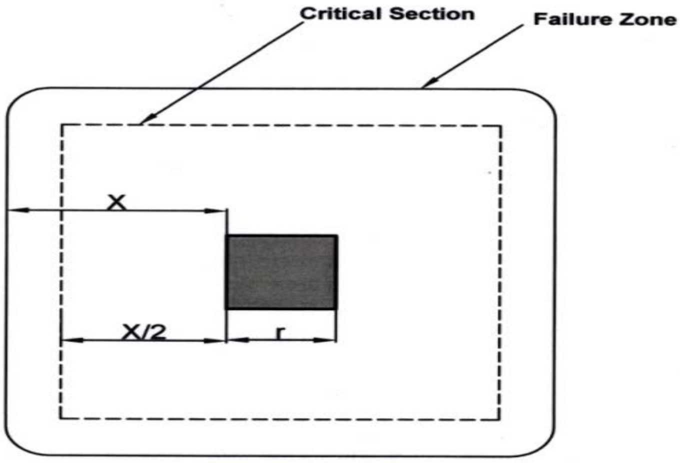

Figure (8) Method Used to Calculate the Critical Sections

$A = r^2 + 4rx + \pi x^2$
$x^2 + 4rx + (r^2 - A) = 0\,\pi$

$$X = \frac{-4r + \sqrt{(4r)^2 - 4 \times \pi \times (r^2 - A)}}{2 \times \pi} \qquad \ldots(1)$$

where:

A: Area of failure zone in (mm^2).
r: Side length of square column.
x: Distance between the end of failure surface and the face of the column.

Table (18) Location of the punching shear section (distance of critical section from face of column)

Slab NO.	Type Of concrete	$f'c$ (MPa)	Steel fiber% by vol.	Thickness (mm)	Measured Failure Area (mm^2)	X (mm) See Figure (7)	Location of punching shear section from face of column			
							Present test@ x/2	ACI318@ d/2	B.S.8110 @1.5 d	CEB-FIP MC-90 @2d
S1	C.C.	30.95	0	50	89207	137.36	68.68	20	60	80
S2	C.C.		0	70	211004	227.8	113.9	29	87	116
S3	C.C.		0	50	101603	148.64	74.32	20	60	80
S4	C.C.		0	70	244029	247.32	123.66	29	87	116
S5	FSCC	32.84	0	50	124651	167.94	83.97	20	60	80
S6	FSCC		0	50	108869	154.94	77.47	20	60	80
S7	FSCC		0	70	267211	260.24	130.12	29	87	116
S8	FSCC		0	70	230874	239.72	119.86	29	87	116
S9	FSCC	34.54	1	70	198829	220.22	110.11	29	87	116
S10	FSCC		1	70	220789	233.74	116.87	29	87	116
S11	FSCC		1	50	92102	140.06	70.03	20	60	80
S12	FSCC		1	50	78989	127.44	63.72	20	60	80
S13	FSCC	39.44	2	70	199205	216	108	29	87	116
S14	FSCC		2	50	80798	129.24	64.62	20	60	80
S15	FSCC		2	50	67205	115.2	57.6	20	60	80
S16	FSCC		2	70	172211	202.8	101.4	29	87	116

The results in Table (18) show that the critical section of the FSCC slabs is located at a distance between 1.6d to 1.9d from the face of column. Also results indicate that as the content of steel fibers becomes higher the critical punching shear section becomes closer to the face of the column indicating that the punching shear area becomes smaller. This does not mean that the punching shear force will be smaller too, but on the contrary it will be greater since a larger punching shear force is usually required to cut or pull out the higher amount of fibers. Increasing slab thickness or flexural steel reinforcement ratio lead to a shift in the punching shear section away from the face of the column. This obviously leads to a larger punching shear area and eventually a higher punching shear force.

Ultimate Punching Shear Stress

It can be seen from the test results in Table (19), that by increasing the volume fraction of fibers from 0% in group2, 1% in group3 and 2% in group4, the ultimate punching shear stress was increased by (4.51%, 52.52% and 97.47%) respectively for slabs with 50mm thickness, as compared with reference slabs of group1.

One can see from the results also that by increasing the volume fraction of fibers from 0% in group2, 1% in group3 and 2% in group4, the ultimate punching shear stress was increased by (10.34%, 43.67% and 96.16%) respectively for slabs with 70mm thickness, as compared with reference slabs of group1. This means that, although the perimeter and effective depth are greater for the 70mm slabs than the 50mm ones, the ultimate punching shear stress is still higher in the former than the latter.

The increased flexural steel reinforcement ratio leads to decreasing percentage rise in the ultimate punching shear stress due to the use of fibers. One can see this drop clearly when increasing the volume fraction of fibers from 0% to 2%. Table (19) shows all results of the ultimate punching shear stress for all tested slabs.

Table (19) Ultimate punching shear stress in slabs

GroupNo.	Slab Designation	ρ	Vf%	P_u (kN)	Effective Depth(d) (mm)	Perimeter of the critical punched section@ x/2 (mm)	Ultimate Punching Shear Stress (MPa)
Group One reference slabs (C.C.)	S1	0.0033	0	52.5	40	749.44	1.75
	S2	0.0033	0	67.5	58	1111.2	1.05
	S3	0.0066	0	57.5	40	794.56	1.81
	S4	0.0066	0	108	58	1189.28	1.56
Group Two (RPC) (FSCC0)	S5	0.0066	0	65	40	871.76	1.86
	S6	0.0033	0	58.5	40	819.76	1.78
	S7	0.0066	0	124	58	1240.96	1.72
	S8	0.0033	0	78	58	1158.88	1.16
Group Three (RPC) (FSCC1)	S9	0.0033	1	95	58	1080.88	1.51
	S10	0.0066	1	148	58	1134.96	2.24
	S11	0.0066	1	84	40	760.24	2.76
	S12	0.0033	1	76	40	709.76	2.67
Group Four (RPC) (FSCC2)	S13	0.0066	2	182	58	1064	2.94
	S14	0.0066	2	102	40	716.96	3.55
	S15	0.0033	2	92	40	660.8	3.48
	S16	0.0033	2	128	58	1011.2	2.18

CONCLUSIONS

1. For the case of 50mm slabs the following was found. With ρ=0.0033 the percentage increase in the ultimate failure load of FSCCC slabs exceeded that of CC ones by (11.43, 44.45 and 75.24)% when FSSCC slabs had V_f of (0, 1 and 2)% respectively, and of the order (13.04, 46.08 and 77.39)%, for FSCC slabs with ρ=0.0066.
2. For the case of 70mm slabs the following was found. With ρ=0.0033 the percentage increase in the ultimate failure load of FSCC slabs exceeded that of CC

ones by (15.55, 40.47 and 89.63)% when RPC slabs had V_f of (0, 1 and 2)% respectively, and of the order (14.81, 37.03 and 66.66)%, for FSCC slabs with ρ=0.0066.

3. The inclusion of steel fibers in all FSCC slabs resulted in a significant enhanced ductility which made the slabs fail gradually in a ductile manner, unlike non-fibrous slabs and/or conventional concrete slabs which showed lesser ductility at failure.

4. The inclusion of steel fibers in FSCC slabs resulted in an enhanced stiffness, reduced crack width, reduced rate of crack propagation and preserving the whole section together after reaching failure. Most of the steel fibers were observed to pullout of the cement matrix rather than snap.

5. The failure angle of FSCC slabs was found to increase with increasing V_f. The highest value was 20.85^o for FSCC slab with 2% steel fibers, while the lowest value was 14.08^o for RPC slab without fibers. This indicates that the size of failure zone can be reduced by adding fibers to the FSCC slabs thus helping to prevent the disintegration of concrete cover under the flexural steel reinforcement.

6. Increasing the volume fraction of steel fiber (V_f) leads to decreased perimeter of the punching shear section. Also increasing slab thickness leads to increased length of such perimeter. The results of the present investigation show that the distance between the face of the column and the critical punching shear section is about (2d) for FSCC slabs with fibers.

7. For the 50mm slabs the following was found. With ρ=0.0033 the midspan deflection at ultimate load is considerably increased by the presence of steel fibers exceeded that of NSC ones by (17.64, 39.1 and 72.66)% when FSCC slabs had V_f of (0, 1 and 2)% respectively, and of the order (17.04, 54.09 and 99.77)%, for FSCC slabs with ρ=0.0066.

8. For of 70mm slabs the following was found. With ρ=0.0033 the midspan deflection at ultimate load is considerably increased by the presence of steel fibers exceeded that of NSC ones by (22.99, 42.66 and 81.3) % when FSCC slabs had V_f of (0, 1 and 2)% respectively, and of the order (28.85, 48.29 and 79.74)%, for FSCC slabs with ρ=0.0066.

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Notations:

ACI	American Concrete Institute
ASTM	American Society for Testing and Material
BS	British Standards
CC	Conventional Concrete
FSSCC	Fiber Self- Compacting Concrete
$f_c^{'}$	Cylinder Compressive Strength of Concrete (MPa)
f_{cu}	Cube Compressive strength of Concrete (MPa)
f_r	Flexural Strength of Concrete (modulus of rupture) (MPa)
d	Effective Depth of Slab (mm)
E_c	Modulus of Elasticity of Concrete (MPa)
P_u	Ultimate Load (kN)
d	Effective Depth of Slab (mm)
V_f	Volume Fraction of Steel Fibers
Vf	Volume Fraction of Steel Fibers
ρ	Steel Reinforcement Ratio