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PUNCHING OF SELF- COMPACTING HIGH STRENGTH REINFORCED CONCRETE FLAT SLABS AT CORNER COLUMN

Wael Nabil[1], Mahmoud El- Kateb[2] and Ayman Khalil[3]
[1] Research Assistant, Structural Engineering Department, El Shorouk Academy, Cairo, EGYPT
[2]Assistant Professor, Structural Engineering Department, Ain Shams University, Cairo, EGYPT
[3]Professor, Concrete Engineering Department, Ain Shams University, Cairo, EGYPT

ملخص البحث:
يقدم البحدث دراسة معملية لسلوك القص الثاقب للبلاطات الخرسانية المسلحة عند اعمدة الركن باستخدام خرسانة عالية المقاومة ذاتية الدمك ويوضح تأثير استخدام تسليح القص من عدمة وعمل مقارنة بين الاكواد المختلفة ومقارنتها بين النتائج المعملية. والوصول الى توصيات تفيد فى التصميم ومقاومة القص الثاقب.

ABSTRACT
Shear reinforcement can be used to maximize the ductility and strength of the reinforced concrete flat slabs. However, to be efficient, the shear reinforcement must be anchored well in the tension and compression zones of the slab. The test results on the slab-column connection models which provided with shear reinforcement are introduced in this research paper. The benefits of using shear reinforcement are to reduce the slab thickness, cost, and weight of the structure.
This paper investigates, experimentally, the behaviour of punching in flat slab at corner column connections made of high strength self-compacting concrete and provided with special shear reinforcement. The slabs having a dimension 1100*1100 mm and 160 mm thickness and loaded at corner column with a single concentrated load until failure.
The general behaviour of the deformation of the tested slab specimens was examined and recorded (cracking, deflection, and strain in both steel and concrete). To calculate the results of the tested specimens, different of international codes had been used to evaluate the strength of the punching shear and confirm that the difference between the international code and experimental results was acceptable.
Recommendations for the experimental analysis and execution for flat slabs were obtained. A comparison had been made between the research test results and the codes equations to improve the methods of the analysis about the flat plates.

1. INTRODUCTION
Flat plate structures of reinforced concrete, i.e. slabs directly supported by columns without any dropped beams, are common in various types of buildings and structures such as office buildings, car park buildings, and bridges. The absence of drop panels or dropped beams simplifies formwork, increases the used space, and reduces the overall height of a building. Since most of the analysis concrete is defined by some characteristics such as cracking and crushing, so the flat slab column connection behaviour under static load can be marked out through them.
One of the most economical systems in reinforced concrete structures is the flat slab. It provides flexibility in the architectural design; which maximize the clear space, minimize the building height, and minimize the construction time. However, the punching failure due to transfer of unbalanced moments and shearing forces between columns and slabs is considered a critical problem in flat slab system. The unbalanced

moment is transferred by the combination of flexure, shear, and torsion in the slab next to column faces. When shear stresses due to shear forces and moment transfer in the region of flat slab next to column become too high, a punching failure will occur.
The reinforced concrete slabs which developed in US. And Europe in 20th century typically included large column capitals looked like mushroom in shape to improve the local introduction of forces from the slab to the column. In 1950, slabs without capitals started to become popular. Because of their construction simplicity therefor they have been used for medium height office, residential buildings, and parking garages. Flat slab design depends on the conditions of serviceability and the ultimate grade of punching shear which called two-way shear.
Since many years ago, punching has been a problem to engineers who tried to fully understand it. It does not matter how many experiments, analysis, and models were made which relied on empiric results that did not describe the totally phenomenon. The test parameters which used are the reinforcement properties, the geometry of the slabs, aggregate size, and loading modes. Although all of these were planned in an intelligent way, providing a huge range of results, it is impossible to cover all parameters. However, this system has a lot of problems which is failure of punching shear of the slabs due to the high concentration of stresses near slab-column connections. This failure type is critical due to its brittle nature. Once, the failure of punching shear occurs, structure resistance is typically reduced due to separation between column and slab therefor joint connection failure will occurs.

2. EXPERIMENTAL PROGRAM

In the design of reinforced concrete structures, strength of members must be adequate to avoid shear failure of the system. Therefore, understanding the shear behavior in reinforced concrete is important. For a flat plate floor system, gravity and lateral loads produce shear forces and moments which must be transferred between a slab and columns. These shear forces and unbalanced moments are the cause of shear stresses in the slab-column connection. So experimental testing is the best mean to investigate the behavior of any structural element failure in a brittle manner. Therefore, it was decided to design an experimental program to test the slabs assemblage, prepare the specimen for this program and undergo the testing program. This part presents the designed test program, details of constructing the specimen (prisms) along with their material properties, and the test procedure.

2.1. PURPOSE OF THE EXPERIMENTAL STUDY

To evaluate experimentally the slab-column connection behavior with and without punching shear reinforcement under concentric vertical load.

2.2. DESCRIPTION OF THE TEST SPECIMENS

Present study consists of two specimens having a dimensions 1100x1100 mm, 160 mm thickness near column, and 220 mm thickness at edge of slab and has column dimension 150x150 mm as shown in Fig. (1). All the details of specimens are listed in Table (1).

Table 1. Matrix of Tested Prisms

Specimen Number	F_{cu}	Reinforcement Slab			Shear Reinforcement
		A	B	C	
SQH	80	6Ø16	3Ø16	9Ø16	No
SQHSH	80	6Ø16	3Ø16	9Ø16	Stirrups 15Ø10 Both Direction

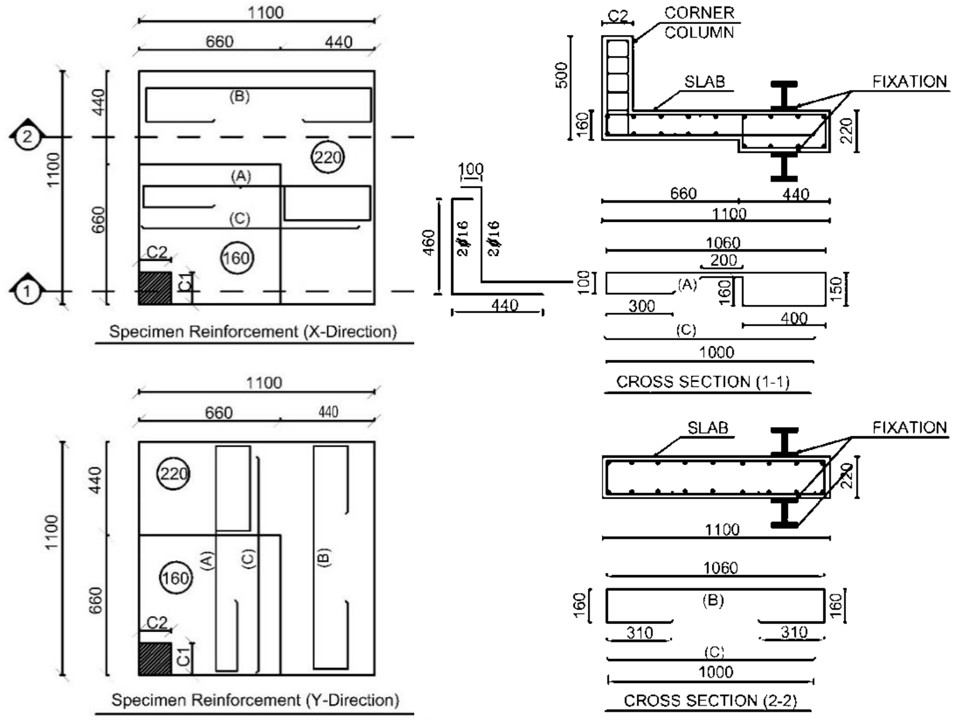

Fig. 1: Reinforcement details of test specimens.

2.3. MIX COMPOSITIONS

The experimental program was carried out at concrete laboratory at faculty of Engineering, Ain Shams University. The concrete mix proportions for all slabs presents in Table (2). A 80 N/mm2 concrete mixture was designed using an Ordinary Portland Cement content of 480 kg/m3 of concrete, silica fume and a super- plasticizer. A water/cement ratio 0.313 had resulted in 700 mm slump. The Coarse aggregate used was washed crushed lime stone with a nominal maximum size 20 mm, while natural sand was used as fine aggregate.

Table 2: Concrete mix proportions to produce (HSSCC).

Cement	Sand	Dolomite	Silica fume	Water	Super Plasticizer	W/C ratio
Kg/m3	Kg/m3	Kg/m3	Kg/m3	Lit/m3	Kg/m3	--
480	750	930	50	150	12	0.313

2.4. INSTRUMENTATION AND TESTING PROCEDURE

The vertical displacement of the slab (deflection) was measured using three LVDTs at center of the column and at distance 0.5L from column as shown in Fig. (2). The measurements were taken after each load increment and they included load from Jack, vertical displacement (deflection) taken from the bottom side of the slab.
After a 28-day curing period, the specimens were positioned on the supporting frame, fixed at the sides that away on the column by using steel beams. The specimens were

tested using single concentric and eccentric load testing condition using 50ton capacity hydraulic jack as shown in Fig. (2). The loading procedure comprised one loading cycle, during which the load was incrementally increased by 5 kN up to the appearance of the first visible crack then the load step rate was increased to 10 kN. At the end of each load step the load was held constant for 1.5-2 minutes during which measurements and observations as well as marking the visible cracks were done.

Fig. 2: Test setup of specimen.

3. EXPERIMENTAL RESULTS

The first crack load, the failure load and the mode of failure for tested specimens are listed in Table (3).

Table 3: Failure and cracking loads for test specimens.

Specimen	First crack Load (KN)	Failure Load (KN)	Failure Type
SQH	84	203	Punching Failure
SQHSH	98	229.39	Punching Failure

3.1. CRACK PATTERN AND PROPAGATION

Crack firstly began at the tension side of the slab and became obvious around (1/3) failure load as shown in Table (3); these cracks form a diagonal shape corresponding to the perimeter of the loaded area. As the used load increased, the cracks width increased and became wider, developing of new cracks that propagate in different directions toward the slab edges creating a van shape. The number, length, and width of the cracks that had been recorded were increasing directly with increasing the applied load.

The test specimens have been designed to fail in punching shear not to fail in flexural moment. The crack patterns of the test slabs are shown in Fig. (3&4). The specimen (SQH) suddenly failed in punching shear with extended falling of tension concrete, while the specimen (SQHSH) that strengthened by shear reinforcement failed in a similar manner showing a ductile and gradual punching failure with higher ultimate loads.

Fig. 3: punching failure for specimen (SQH)

Fig. 4: punching failure for specimen (SQHSH)

3.2. DEFORMATIONAL BEHAVIOR

To study the Realistic simulation for deflection, the relative deflection between deflection under column and deflection at distance 0.5L from column was calculated. Referring to Fig. (5&6), the specimen (SQHSH) had ultimate load value higher than specimen (SQH). At the first crack the applied load for the specimen (SQHSH) with associated relative deflection 4.16 mm was 98 KN while the applied load for the specimen (SQH) with associated relative deflection 4.32 mm was 84 KN. For specimen (SQHSH) at ultimate load level equal 229.40 KN, the recorded relative deflection was 9 mm. While specimen (SQH) at ultimate load level equal 203 KN, the recorded relative deflection was 14.30 mm. The ultimate load of the specimen (SQHSH) was 13 % higher than the specimen (SQH), While the relative deflection at ultimate load level for the specimen (SQH) was 78.75% higher than the specimen (SQHSH) at same loading level.

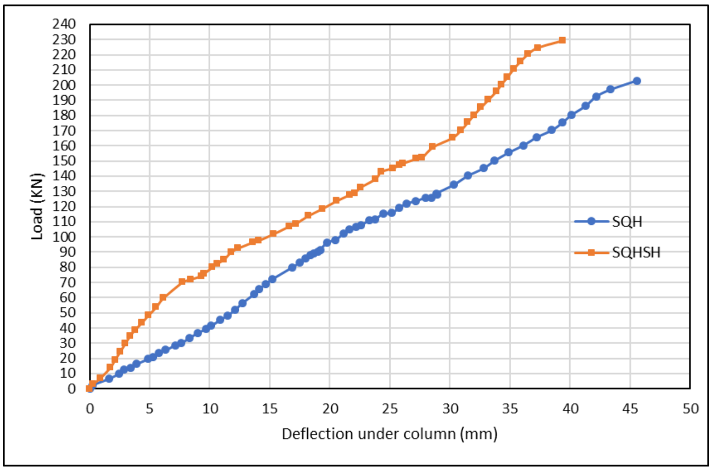

Fig. 5: Load-Deflection Curve for Specimens SQH & SQHSH (Under Column)

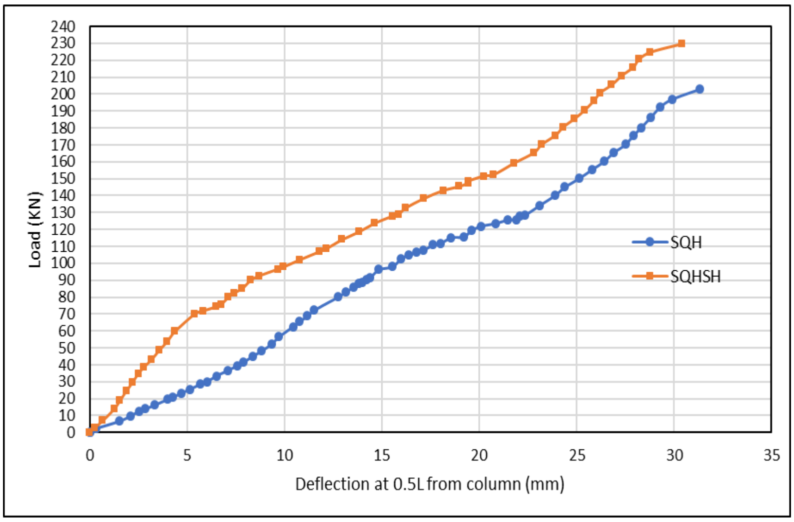

Fig. 6: Load-Deflection Curve for Specimens SQH & SQHSH (at distance 0.5L from column).

4. PROVISIONS CODES

In this part a comparison between the values of ultimate shear stress obtained by the experimental investigation and the values deduced by using the expressions proposed in the codes are carried out.

4.1. Proposed Egyptian code (ECP 203-2017) [1].

The final Egyptian Code practice for design and construction of RC structures considered that the punching shear stress is not to be resisted by concrete only but also by shear reinforcement (vertical stirrups). The Egyptian Code recommends that the critical section for punching shear in slab is at a distance d/2 around the circumference of the concentrated load. According to the comparison of ECP 203-2017 code provision, this comparison listed in table (4), comparison concrete punching shear strength (q_{cup}) which calculated by the test specimen (SQH), where does not contain shear reinforcement and nominal shear strength (q_{up}) with the rest of the test specimen (SQHSH) where contain shear reinforcement (vertical stirrups). The conservatism degree increases with using shear reinforcement.

Table (4): Comparison between ECP Predicted Shear Load and Test Failure Load

specimen	F_{cu} Mpa	Shear Reinforcement	P_{test} ton	P_{ECP} ton	P_{test}/P_{ECP}
SQH	80	No	203	104.72	1.94
SQHSH	80	Vertical Stirrups 15Ø10 Both Direction	229.39	133.69	1.71

4.2. Comparisons with ACI Code 318-08 [2].

The capacity of the punching shear that specified on ACI 318-08 will be calculated on a perimeter of a distance d/2 from the face of the column for all sides in square or rectangular columns. On the other hand, for square or rectangular corner columns the critical section will be taken from two sides. According to the comparison of ACI 318-08 code provision, this comparison listed in table (5), comparison concrete punching shear strength (V_{uo}) which calculated by the test specimen (SQH), where does not contain shear reinforcement and nominal shear strength (V_n) with the rest of the test specimen (SQHSH) where contain shear reinforcement (vertical stirrups). The conservatism degree minimizes with using shear reinforcement.

Table (5): Comparison between ASI Predicted Shear Load and Test Failure Load

specimen	F_{cu} Mpa	Shear Reinforcement	V_{test} ton	V_{ACI} ton	V_{test}/V_{ACI}
SQH	80	No	203	162.624	1.25
SQHSH	80	Vertical Stirrups 15Ø10 Both Direction	229.39	151.379	1.51

4.3. Comparisons with BS 8110-97 British standard [3].

The capacity of the punching shear will be calculated on a perimeter of a distance 1.5d or more from the loaded area (column). The failures of the punching shear occur on the inclined faces of the pyramid or truncated cones, depending on the loaded area shape. According to the comparison of BS 8110-97 code provision, this comparison listed in table (6), comparison concrete punching shear strength (V_{cd}) which calculated by the test specimen (SQH), where does not contain shear reinforcement and nominal shear strength (V_{sd}) with the rest of the test specimen (SQHSH) where contain shear reinforcement (vertical stirrups). The conservatism degree increases with using shear reinforcement. By adding the top main reinforcement (9Ø16) to the design equation (ρ) maximizes the resistance of the punching shear in the experimental specimen test results.

Table (6): Comparison between BS Predicted Shear Load and Test Failure Load

specimen	F_{cu} Mpa	Shear Reinforcement	V_{test} ton	V_{BS} ton	V_{test}/V_{BS}
SQH	80	No	203	165.715	1.22
SQHSH	80	Vertical Stirrups 15Ø10 Both Direction	229.39	186.72	1.23

4.4. Comparisons with Eurocode 2 [4].

According to Eurocode 2, the critical section should be at distance 2d from the face of the loaded area for interior, edge and corner column and should be constructed as to minimize its length. But in case of using shear reinforcement the recommended section is 1.5d. According to the comparison of Eurocode 2 provision, this comparison listed in table (7), comparison concrete punching shear strength (V_{rd}) which calculated by the test specimen (SQH), where does not contain shear reinforcement and nominal shear strength (V_{rdcs}) with the rest of the test specimen (SQHSH) where contain shear reinforcement (vertical stirrups). The conservatism degree decreases with using shear reinforcement. By adding the top main reinforcement (9Ø16) to the design equation (ρ) maximizes the resistance of the punching shear in the experimental specimen test results.

Table (7): Comparison between EN Predicted Shear Load and Test Failure Load

specimen	F_{cu} Mpa	Shear Reinforcement	V_{test} ton	V_{EN} ton	V_{test}/V_{EN}
SQH	80	No	203	162.818	1.25
SQHSH	80	Vertical Stirrups 15Ø10 Both Direction	229.39	172.701	1.32

5. CONCLUSION

According to the experimental investigation results which were executed in this research study, the following important conclusions:

- The slab specimens that provided by shear reinforcement (vertical stirrups) lead to increase the resistance of punching shear for slab-column joints with ratio 13% for. While the relative deflection decreases with ratio 78%.
- The internationals and local codes that have been selected to study in our research gives conservative estimate for the punching shear capacity of tested slab.
- Depending on the BS code provision, adding the top main flexural reinforcement steel factor (ρ) in our design code equations will led to increase the resistance of the punching shear of the slab-column connections.
- Depending on the different national and international code provisions, the ACI, and ECP codes show lower resistance of the punching shear than the BS, Eurocode by not adding the top main reinforcement in their design equations.

6. REFERENCES

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