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Fracture Analysis of Punching Shear in Flat Slab with Conventional Punching Shear Reinforcement and Steel Fiber using FEA Software

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***Abstract*—One of the major problems in the RCC flat slab is the punching shear failure of the slab-column connection. This type of failure must be avoided. The codal provisions for the analysis and design of RCC flat slab are mostly based on empirical and statistical formulations which are derived from the tests done by the past researchers [1], require a compromise between the material cost and time to experimentally analyze punching shear failure for different cases of slab column connection. The present study focuses on the FEA based analysis of Interior slab-column connection. The finite element analyses (FEA) will supplement the present testing and it can be used for constant investigation, since it can indicate different aspects of punching shear failure, leading to possible recommendations for planning codes and models. This study investigates the punching shear behavior of two-way RCC flat slabs with HYSD bars as flexural reinforcement. Analysis of punching shear capacity of RCC flat slab using FEA software for an Interior slab-column connection has been presented in this paper. Simulation of slab-column connections with conventional punching shear reinforcement and steel fiber as punching shear resistance and with shear bolt as shear reinforcement has been done and a comparative study has been made in regard to their punching shear resistance efficiency.**

Keywords—Displacement, Fracture energy, Flat plate slabs, and Punching shear strength.

I. INTRODUCTION

Reinforced concrete flat slabs are commonly used structural system as it has many advantages like they offer a simple formwork, increased floor height, and lower construction cost. However, high stresses are developed at the connection between the slab and the supporting columns due to the lack of horizontal supporting members such as beams and girders (fig.1). These stresses can result in a brittle failure mode known as punching shear. Due to its brittle nature, punching shear failure of a single slab-column connection can lead to the progressive collapse of a portion of an entire structure if the slab reinforcement is not properly designed or detailed (fig. 2). According to current regulations given in code ACI 318-14, even when calculations prove that the slab does not require to be reinforced against punching shear, the reinforcement still must be placed within the bottom zone of the flat slab so as to prevent progressive structural collapse even in case of other external forces. This reinforcement can be in the form of straight or bent bars (fig. 3) [1].

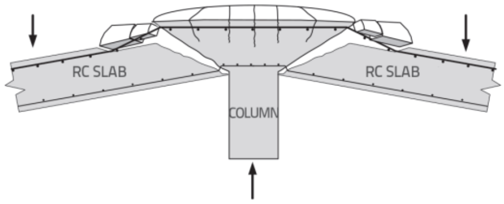

Fig. 1, Schematic view of punching in case of slab supported on columns only [2]

Fig. 2, Top story collapse at the public car park in Wolverhampton (UK)[3]

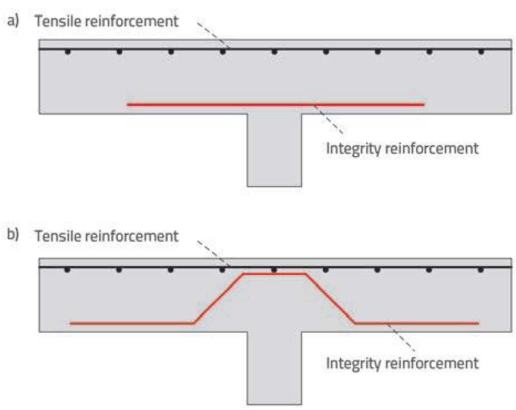

Fig. 3, Integrity reinforcement in the form of straight and bent bars[2]

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The shear failure in RCC Flat slab elements without shear reinforcement is directly related to the tensile strength of concrete, which is most often defined as a function of compressive strength [4]. In 1930s Graf established that no linear relationship exists between the resistance against the punching shear of the slab - column connection and the compressive strength of concrete [5].

A. *Codal provisions for punching shear strength*

The following regulations for the design of concrete structures were selected to enable comparison with results of the experiments conducted in the scope of this research: Indian Standard code IS 456 [6] (fig. 4), American Concrete Institutes code ACI Code 318-14 [1] (fig. 5).

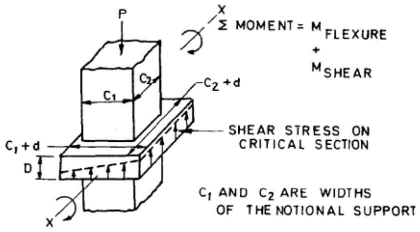

Fig. 4, Transfer of moment to Column as per IS 456-2000 [3]

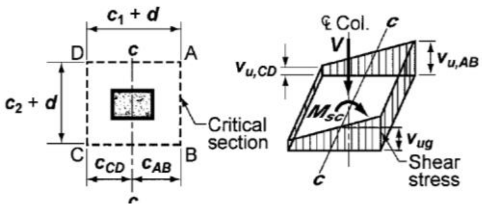

Fig. 5, Transfer of moment to Column as per ACI 318-14 [4]

Taking into account the provisions presented in code [1], [6] the punching shear strength is calculated according to the following expressions:

- IS 456-2000: $\tau_c = (0.5 + \beta_c) 0.25\sqrt{f_{ck}}$
- ACI 318-14: Least of (a),(b), and (c)

a) $\tau_c = 0.33\lambda\sqrt{f'_c}$

b) $\tau_c = 0.17(1 + \frac{2}{\beta_c})\lambda\sqrt{f'_c}$

c) $\tau_c = 0.083(2 + \frac{\alpha_s d}{b_0})\lambda\sqrt{f'_c}$

B. *ACI 318-14 code provisions details for Interior slab*

Punching shear failure involves the formation of a truncated cone (or pyramid shape) of cracks forming around the base of the slab at the Interior column connection. Punching shear reinforcement works to overcome the inclined cracks which are form inside the slab due to tensile forces. Arrangement of stirrup shear reinforcement as per ACI 318-14 is shown in fig. 6 [1].

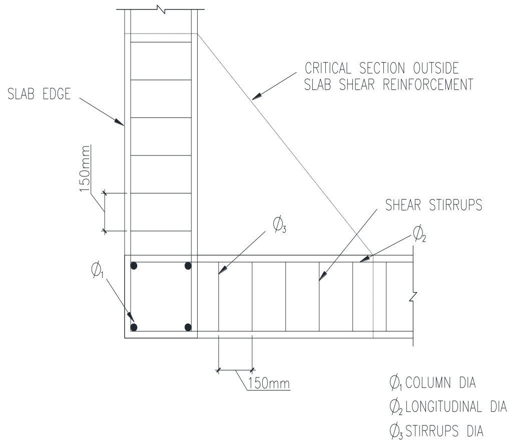

Fig. 6, Arrangement of stirrup shear reinforcements as per ACI 318-14

C. *shear bolt arrangement for Interior slab*

In the past shear bolt has been used in slabs to resist the punching shear failure [7]. For the present study, the arrangement of a shear bolt as shear reinforcement is shown in fig. 7. The tensile forces opening shear cracks in the slab are transferred through shear bolts.

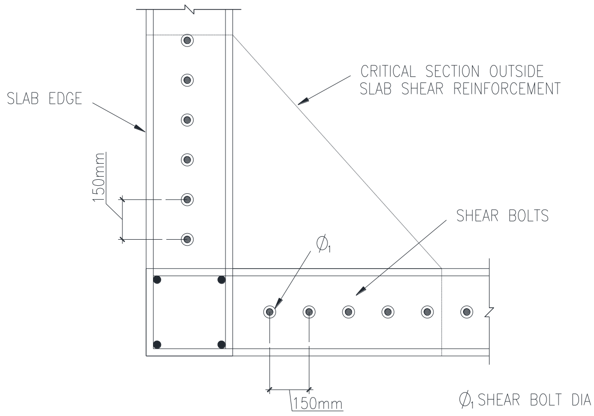

Fig. 7, Arrangement of shear bolts as shear reinforcements

D. *Steel fiber as punching shear reinforcement in interior slab*

Fig. 8: Steel Fiber

II. MATERIALS AND METHODOLOGY

The material properties for three slab-column specimens (SB1, SB2, and SB3) used for this study are presented in Table 1.

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TABLE I. MECHANICAL PROPERTIES OF MATERIALS FOR SB1, SB2, AND SB3

Slab Type	Table Column Head									
	Concrete			*Main Reinf.*			*Shear Reinf.*			
	E (MPa)	V_{12}	ρ (kg/m^3)	E (MPa)	V_{12}	ρ (kg/m^3)	E (MPa)	V_{12}	ρ (kg/m^3)	Tensile Strength
SB1(shear stirrups)	25000	0.2	2500	200000	0.3	7850	200000	0.3	7850	500
SB2 (shear bolt)										500
SB3 (steel fiber)										1225

Three slab-column specimens (SB1, SB2, and SB3) are analyzed.

Case I: Interior column with shear reinforcement as per ACI 318-14 provisions (SB2)

Case II: Interior column with shear bolt as shear reinforcement (SB3) as depicted in fig.7

Case III: Interior column with steel fiber as punching shear reinforcement (SB3)

The boundary condition for the slabs is shown in fig.9. All three slabs are tested for a constant value of load equal to 20 kN/m^2 and the punching shear stress response for all three cases has been studied.

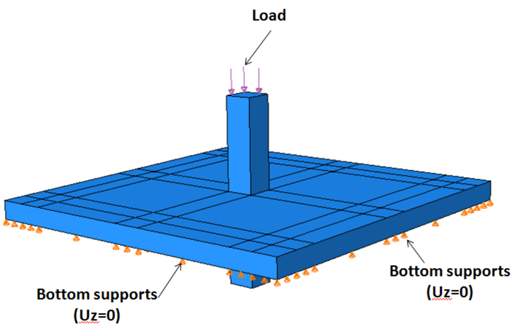
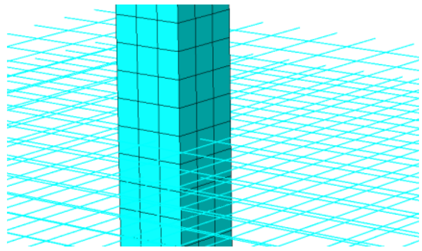


Fig. 9, Geometry and Boundary Conditions for Interior Column-slab Connection

The slab SB1 is an Interior column without shear reinforcement shown in fig. 10(a), the slab SB2 is Interior column with shear reinforcement as per ACI 318-14 shown in fig. 10(b) and the slab SB3 is an Interior slab-column connection with shear bolt as shear reinforcement shown in fig. 10(c). The reinforcement

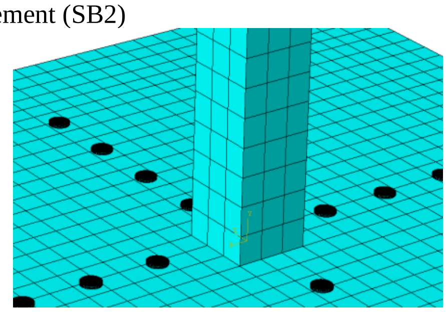
In the slab-column specimens (SB2 and SB3) shown in fig. 10(b) and fig 10(c) have been modeled as per the reinforcement details are given in fig.6 and fig.7 respectively.

Case I: Flat slab with shear reinforcement as per ACI 318-14 (SB1)



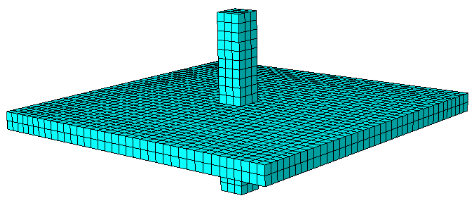
(a) SB1: Interior column with shear reinforcement as per ACI 318-14

Case II: Flat slabs with shear bolt as shear reinforcement (SB2)



(b) SB2: Interior column with shear bolt as shear reinforcement

Case III: Flat slabs with steel fiber as shear reinforcement (SB3)



(c) SB2: Interior column with steel fiber as punching shear reinforcement

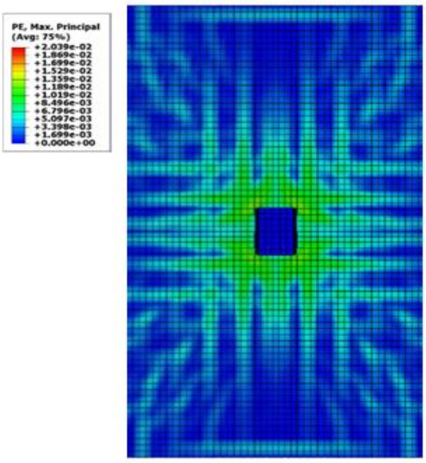
Fig. 10, Reinforcement in the slab-column specimens (SB1, SB2, and SB3)

III. RESULT AND DISCUSSION

FEM based analysis was performed for all the three cases SB1, SB2, and SB3. The Stress concentration around the Interior column in the flat slab it's very high. It starts tangentially near the column and then extends radially toward the slab edges at the constant load. The stress concentration around the Interior column in the flat slab creates potential cracks initiation sites and eventually its leads the punching shear failure.

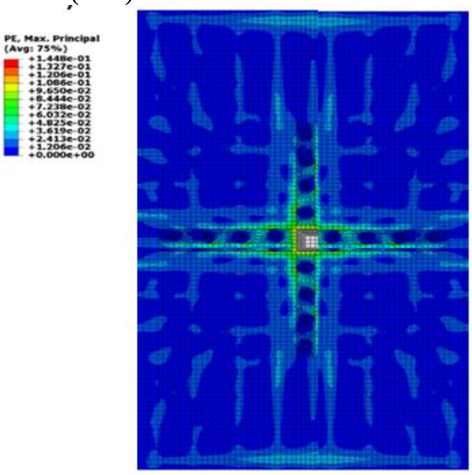
The concrete damaged plasticity model assumes that the cracking initiates when the maximum principal plastic strain is positive [8]. The distribution of maximum principal stress (σ33) in SB1, SB2, and SB3 slab-column connection is presented in fig. 11(a), fig. 11(b) and fig.11(c) respectively.

Case I: Flat slab with shear reinforcement as per ACI 318-14 (SB1)



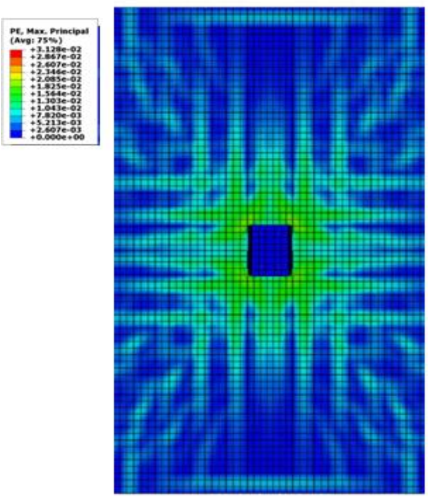
(a) SB1: Stress distribution and crack Patten for slab-column connection with shear reinforcement as per ACI 318-14

Case II: Flat slabs with shear bolt as shear reinforcement (SB2)



(b) SB2: Stress distribution for slab-column connection with shear bolt as punching shear reinforcement

Case III: Flat slabs with steel fiber as shear reinforcement (SB3)



(c) SB3: Stress distribution for slab-column connection with steel fiber as punching shear resistance

Fig, 11, Stress distribution in the slab-column specimens (SB1, SB2, and SB3)

The comparison between three cases in terms of load-deflection and a potential site for crack initiation for Interior slab-column connection shown in table 2, And also it can be seen that it provides more punching shear reinforcement in Interior slab-column connection increased punching shear capacity and reduces deformation w.r.t fig 11 and table 2.

TABLE II. DISPLACEMENT AND PRINCIPAL STRESSES IN FLAT SLAB

Type	CASES		
	CASE I	***CASE II***	***CASE III***
Max. Principal Stress(σ_{33})	31.11 MPa	25.24 MPa	20.36 MPa
Displacement in Z –dir.	8.90 mm	7.54 mm	6.79 mm

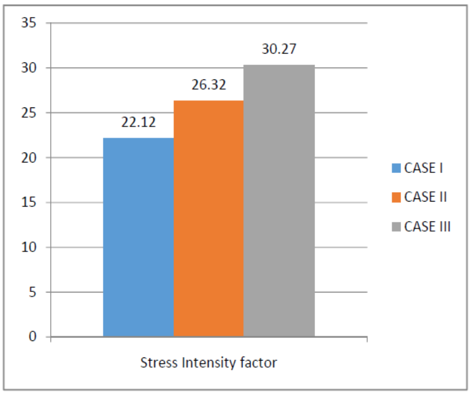


Figure 12: Stress intensity factor for flat slab having Interior column

IV. CONCLUSION

The presented study investigates the behavior of Interior slab column connection under concentrated load. As the punching shear reinforcement is increased (SB2 and SB3), potential site for crack initiation seen to reduced around the Interior column area.

Flat Slabs strengthened with shear reinforcement exhibited punching shear forces that were on an SB2 and SB3 are 14.27 % and 39.56 % respectively greater resistance to the Interior slab-column connection without shear reinforcement. Also, the displacement resistance increased in SB2 and SB3 are 12.90 % and 36.46% respectively to the Interior slab-column connection without shear reinforcement.

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