PUNCHING OF HIGH STRENGTH CONCRETE FLAT SLABS – EXPERIMENTAL INVESTIGATION

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Abstract

An experimental research was conducted to investigate the punching behaviour of high strength concrete (HSC) flat slabs, presenting a compressive concrete strength of 130 MPa. The tested specimens were 1650 mm square and 125mm thick and had different longitudinal reinforcement ratios varying between 0.94% and 1.48%. The central column was simulated thru a steel plate 200 mm square. The punching capacity of slabs made of HSC was up to 43% higher than that of a reference model made with normal strength concrete (35.9 MPa). The experimental results were compared with the code provisions by EC2, ACI 318-11 and MC2010.

Keywords: High Strength Concrete (HSC), Punching, Flat Slabs

1 Introduction

High strength concrete (HSC) has continuously evolved in the last few decades and in recent years, the use of HSC in structures has increased significantly. In spite of the growing use of HSC in building construction, the information available on the structural performance of this material is reduced, and the amount of experimental tests that has been carried out regarding the study of the behaviour of HSC slab-column connections is still limited. Additionally, most of the existing experimental studies on this subject, adopted concrete compressive strengths that were under 90MPa, (Marzouk and Hussein, 1991), (Tomaszewicz, 1993), (Hallgren, 1996), (Ramdane, 1996), (Vargas, 1997), (Ghannoum, 1998), (Marzouk, Emam and Hilial, 1998), (Ozden, Ersoy and Ozturan, 2006) and (Yasin and Smadi, 2007).

In this study, an experimental research was conducted on four specimens to investigate the structural behavior of HSC slab-column connections with a concrete compressive strength of 130 MPa. The structural behavior regarding the evolution of deformations and punching capacity of HSC slabs with different reinforcement ratios (0.94 to 1.48%) is presented.

2 Experimental program

2.1 Specimens

The experimental program consisted in testing four reduced scale flat slab specimens up to failure by punching. Three of these were cast with HSC and the remaining one was cast with normal strength concrete (NSC), whose objective is to be used as a reference slab.

The specimens were named based on strength concrete class (NS for normal strength and HS for high strength) and on its longitudinal reinforcement ratio. Thus, specimens HS1, HS2 and HS3 were built with HSC and with a reinforcement ratio of 0.94%, 1.24% and 1.48%, respectively. Specimen NS was cast with NSC and with a reinforcement ratio of 1%.

The specimens measured 1650x1650 mm^2 with a thickness of 125 mm. They modeled the area near a column of an interior slab panel up to zero moments line. The slab bottom flexure reinforcement consisted on a square mesh of 6 mm diameter bar spaced at 200 mm and the top reinforcement is presented in Table 1. During the specimens production the average effective depths of longitudinal reinforcement were measured which are also presented in Table 1.

2.2 Test setup and monitoring

The specimens were subjected to a central monotonic loading up to failure using a hydraulic jack with a capacity of 1000 kN positioned under the slab. The load was applied at rate of 0.25 kN/s through a square steel plate with 200 mm sides and 50 mm thickness. The slabs were fixed to the strong floor of the laboratory in eight points, using four steel tendons and spreader beams according to Figure 1.

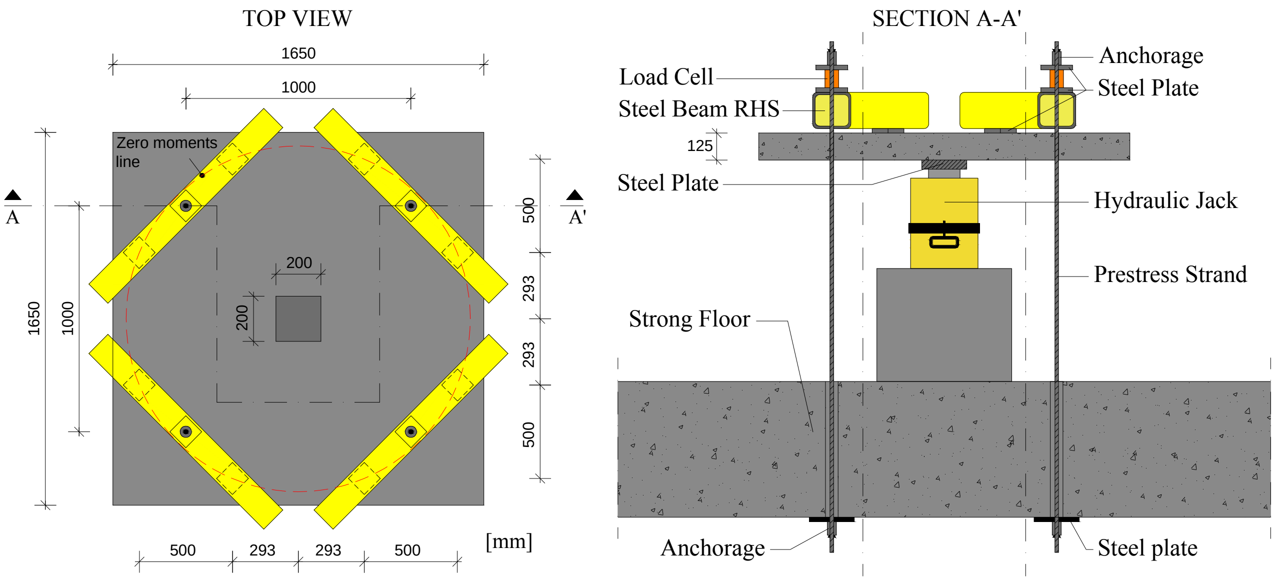

Fig. 1 Test geometry.

Loads, displacements and strains in the top longitudinal reinforcement bars were recorded at every second of loading by means of an electronic data acquisition system connected to a computer.

Vertical deflections of test specimens were measured at eleven different points using linear variable differential transformer (LVDT's) with a displacement stroke of 100 mm. The LVDT D1 was placed in the center of the specimens. LVDT's D2 to D7 were placed in direction of higher effective depth, while LVDT's D8 to D11 were perpendicularly placed. LVDT's D4, D5 and D3, D6, D9, D10 were placed at a distance of 1.25*d* and 2.5*d*, respectively, from the column's face. LVDT's D2, D7, D8 and D11 were located in the zero moments line (Figure 2).

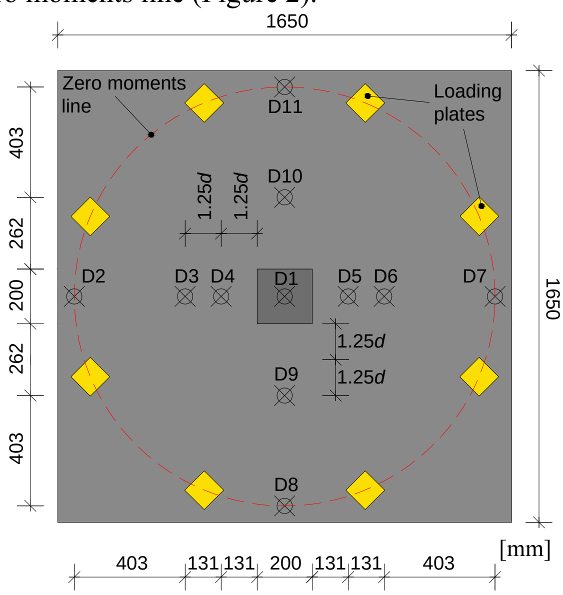

Fig. 2 LVDT's and loading plates position.

Four rebars of the top longitudinal reinforcement were monitored using pairs of diametrically opposed strain gauges, which were glued in the middle section.

The vertical load applied to the specimen was measured by four load cells, one for each steel tendon, which fixed the specimen to the strong floor (Figure 1).

2.3 Materials

Twelve 150x300 mm^2 cylinders were casted for each specimen and used to determine the average compressive strength (f_{cm}) and the average splitting tensile strength of concrete ($f_{ctm,sp}$). The compression and splitting tests were performed in the same day of the respective slab specimen test, according to (EN 12390-3, 2003) and (EN 12390-6, 2003), respectively. The average values are listed in Table 1, together with the 0.2% proof strength ($f_{0.2}$) and ultimate strength (f_t) of the longitudinal reinforcement steel that were determined according to (EN 10002-1, 2006).

Table 1
Characteristics of the specimens and materials properties

Specimens	ρ (%)	d (mm)	Concrete		Top Reinforcement			Bottom Reinforcement	
			f_{cm} [MPa]	$f_{ctm.sp}$ [MPa]	Mesh	$f_{0.2}$ [MPa]	f_t [MPa]	$f_{0.2}$ [MPa]	f_t [MPa]
NS	1.00	105.0	35.9	3.4	Ø10//75 mm	523.0	607.0	594.0	724.0
HS1	0.94	104.2	125.6	7.7	Ø10//80 mm	493.5	643.9	549.7	697.3
HS2	1.24	101.6	130.1	8.4	Ø12//90 mm	523.4	671.4	549.7	697.3
HS3	1.48	101.7	129.6	8.3	Ø12//75 mm	523.4	671.4	549.7	697.3

3 Tests results

3.1 Vertical displacements

Figure 3 presents the evolution of vertical displacement along the loading for all specimens, using the relative displacements computed between the mean of D8-D11 LVDT's and D1 (Figure 2).

In the HSC specimens the beginning of development of flexural cracking occurs for a load around 130 kN while in the NSC specimen occurs for a load around 50 kN. This behavior is related to the greater tensile strength of HSC. As expected, all specimens exhibited a decrease of stiffness when the flexure cracks starts to form and develop. Furthermore, before cracking, the stiffness of the HSC specimens was slightly higher than of the NSC specimen.

The tests results also showed a displacements decrease at failure with the increase of the longitudinal reinforcement ratio, while stiffness increased slightly.

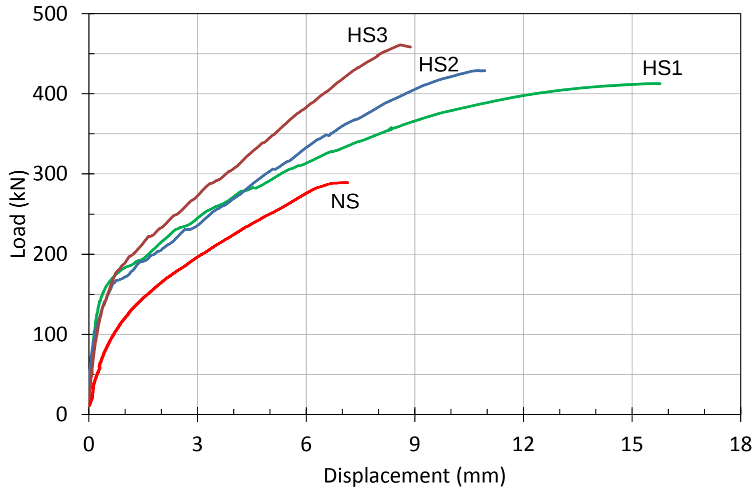

Fig. 3 Load-displacement evolution for all specimens.

3.2 Punching capacity

Table 2 and Figure 5 presents the experimental failure loads (V_{exp}) including self-weight. All tested specimens failed by punching. Figure 4 presents pictures of a tested specimen after punching.

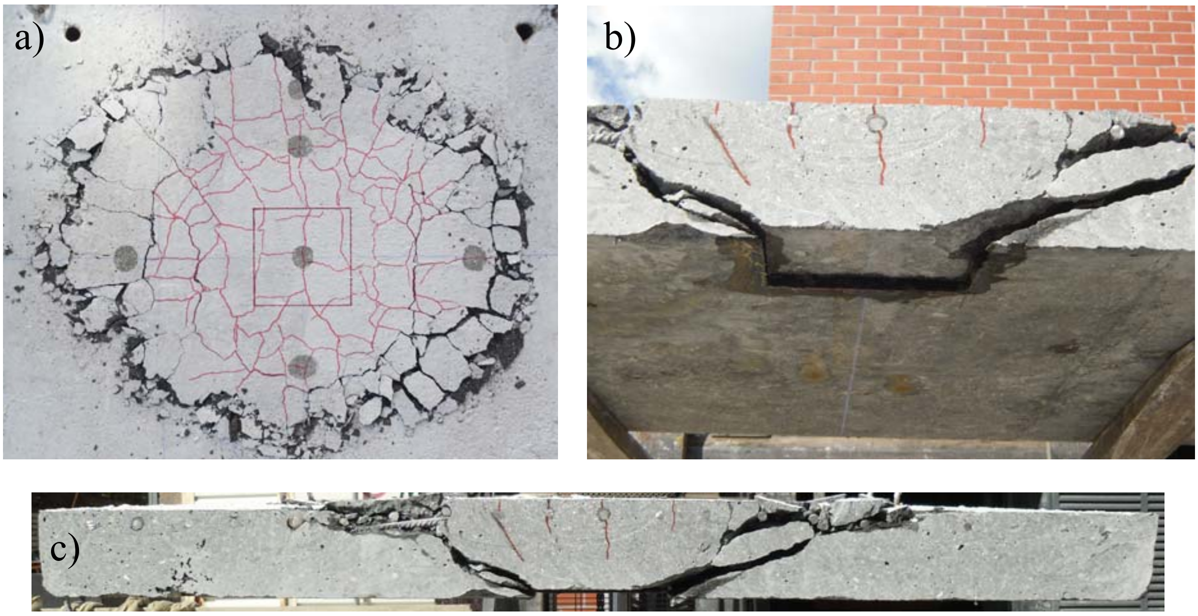

Fig. 4 a) top view, b) saw cut bottom view and c) saw cut of tested specimen HS3.

From the results obtained, and for this set of tests, it is possible to conclude that the use of HSC instead of NSC led to an increase up to 43% of the punching capacity. The increase of reinforcement ratio from 0.94% to 1.48% led to an increase of punching capacity of 12%.

Table 2
Experimental loads

Specimen	NS	HS1	HS2	HS3
V_{Exp} (kN)	289.2	412.9	429.0	460.9

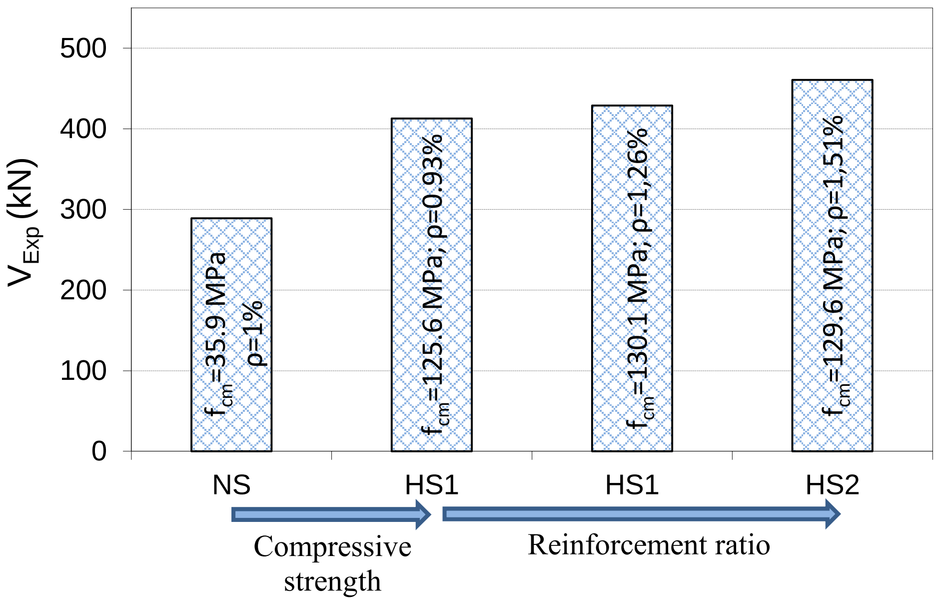

Fig. 5 Experimental loads.

4 Comparison between experimental failure loads and code provisions

In this section the experimental punching forces obtained are compared with the predictions of (EC2, 2004), (ACI 318-11, 2011) and (MC2010, 2012). In the quantification of the punching resistance the mean values for the properties of materials were used and the partial safety coefficients were not considered.

The resistance without punching shear reinforcement, using (EC2, 2004) was computed with the following expression (Equation (1)):

$$V_{Rm} = 0{,}18 \cdot k \cdot \left(100 \cdot \rho \cdot f_{cm}\right)^{1/3} \cdot u \cdot d \tag{1}$$

The limitation of the parameter $k = \left(1 + \sqrt{200/d}\right)$ in (EC2, 2004) to a maximum of 2 was neglected.

For the calculation of the resistance without punching shear reinforcement using (ACI 318-11, 2011), the relevant expression for square columns, with side lengths less than 4d is (Equation (2)):

$$V_{Rm} = \frac{\sqrt{f_{cm}} \cdot u \cdot d}{3} \tag{2}$$

Recently, it was published the final draft of (MC2010, 2012). Punching design recommendations in (MC2010, 2012) present a new design philosophy based on the critical shear crack theory described in (Muttoni, 2008) for slabs without transverse reinforcement. In the following are presented the expressions for the average values that can be compared with the experimental results. According to (Muttoni, 2008), for slabs without transverse reinforcement the punching loads can be compute by (Equation (3)):

$$V_{Rm} = \frac{3/4 \cdot u \cdot d \cdot \sqrt{f_{cm}}}{1 + 15 \dfrac{\psi \cdot d}{16 + d_g}} \tag{3}$$

Where u is the control perimeter defined at d/2 of the edge of the column, ψ is the slab rotation and d_g is the maximum aggregate size (in the present case d_g = 13.9 mm). The rotation of the slab ψ may be obtained for level III approach by (Equation (4)):

$$\psi = 1.2 \cdot \frac{r_s}{d} \frac{f_y}{E_s} \cdot \left(\frac{m_s}{m_R}\right)^{1,5} \quad \text{if} \;\; m_s \le m_R \tag{4}$$

Where m_s is calculated from a linear elastic model as the average value of the moment for design of the flexural reinforcement over the width of the support ((Nielsen, 1999) and (Gualdalini, Burdet and Muttoni, 2009)); m_R is the average flexural strength per unit width in the support strip and r_s stands for the position where the radial bending moment is zero with respect to the column axis.

Figure 6 gives the ratio between experimental failure loads and the predicted values (V_{Exp}/V_{Rm}) using (EC2, 2004), (ACI 318-11, 2011) and (MC2010, 2012) for level III of approach. Table 3 presents the average and the coefficient of variation (CoV) for the ratio V_{Exp}/V_{Rm}, considering all specimens (left values) and when only HSC specimens are considered (right values).

From the presented results it may be observed that both, (EC2, 2004) and (MC2010, 2012), provide a good prediction of the failure load for specimen NS. However, the predicted value obtained for specimen NS using (ACI 318-11, 2011) is somewhat conservative.

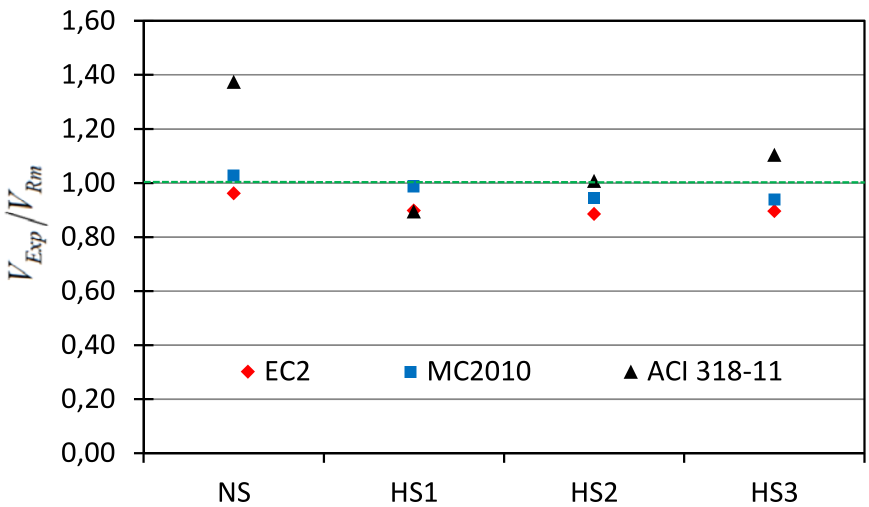

Fig. 6 Ratio between experimental loads and predicted values using codes for all specimens.

When considering only the specimens cast with HSC, it may be concluded that both, (ACI 318-11, 2011) and (MC2010, 2012) leads to a good prediction of punching capacity, for this set of experimental tests, but (ACI 318-11) presents higher values for CoV. The predicted values using (EC2, 2004) are slightly against safety. Additionally (ACI 318-11, 2011) shows a trend of higher ratios of V_{Exp}/V_{Rm} as the ratio of longitudinal reinforcement increases, because its formulation does not take into account the amount of longitudinal reinforcement, contrary to the provisions from (EC2, 2004) and (MC2010, 2012).

Table 3
Resumed results of the obtained relations V_{Exp}/V_{Rm}[a]

Code	EC2	ACI 318-11	MC2010 (III)
Average	0.91 / 0.89	1.09 / 1.00	0.97 / 0.96
CoV	0.04 / 0.01	0.19 / 0.10	0.04 / 0.03

[a] All specimens / only HSC specimens

5 Conclusions

This paper presents an experimental investigation conducted to analyze the punching behaviour of HSC flat slabs. The tests results showed that the punching capacity of flat slabs is substantially increased with the use of HSC, but the rupture is also more brittle when comparing with NSC slabs. The use of HSC led to an increase up to 43% of the punching capacity, when compared with the NSC specimen. The increase of reinforcement ratio led to a slight increase of the punching capacity.

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