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Punching of high strength concrete flat slabs without shear reinforcement

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ABSTRACT

The experimental research carried out to study the punching behavior of high strength concrete (HSC) flat slabs is reported in the present work. Three flat slab specimens were cast using HSC and another one with normal strength concrete (NSC), to be used as a reference slab. The HSC mix presented a compressive strength of about 130 MPa, with a basalt coarse aggregate. The tested specimens were square with 1650 mm side and 125 mm thickness. The longitudinal reinforcement ratio varied between 0.94% and 1.48%.

The experimental results show that the use of HSC led to a significant load capacity increase when compared with the reference model made with NSC. Furthermore, the experimental results also indicated that as the longitudinal reinforcement ratio increased, the punching capacity also increased. The results obtained in this set of experimental tests and others collected from the literature were compared with the code provisions by EC2, MC2010 and ACI 318-11.

1. Introduction

Reinforced concrete flat slabs are a structural solution widely used nowadays for office, commercial and residential buildings. They present several advantages such as the much reduced and simpler formwork, easy installation of mechanical and electrical infrastructures, the versatility and easier space partitioning and faster site operations, which makes flat slabs an economical and efficient structural system. However, they present a complex behavior which may lead to a punching failure. One of the most important subjects in the design of concrete flat slabs is the punching capacity, being frequently the governing factor in choosing its thickness.

The high strength concrete (HSC) technology has continuously evolved in the last few decades. In recent years the use of HSC has increased significantly for different structural applications such as bridges, offshore structures and buildings. Despite the growing use of HSC, the information available on its structural performance is reduced, particularly with concrete compressive strengths above 90 MPa, and the punching phenomenon is not an exception.

There are several experimental studies on the punching behavior of HSC slabs, but most of them adopted concrete with compressive strengths under 90 MPa [1–12]. In the referred, works only nine specimens were tested wherein the concrete compressive strength was greater than 90 MPa and only five of them had more than 100 MPa. Previous works conducted to investigate punching shear behavior showed that increasing the concrete compressive strength resulted in an improvement in structural performance. The punching capacity increases with the increase in concrete strength and alongside the slab stiffness is also higher [13]. High strength concrete slabs usually exhibited a more brittle failure than normal strength concrete flat slabs.

2. Experimental research

The experimental program consisted in testing four reinforced concrete flat slabs specimens, three with HSC and another one with normal strength concrete (NSC), under concentric and monotonic increasing punching load. The concrete strength used ranged between 35.9 MPa (NSC) and 130.1 MPa (HSC), while the average longitudinal reinforcement ratios varied between 0.94% and 1.48%.

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Nomenclature

ρ	longitudinal reinforcement ratio
ψ	slab rotation
ε_y	yield strain of steel reinforcement
c	column side dimension
d	average effective depth
d_g	maximum aggregate size
d_v	shear-resisting effective depth
f_c	mean value of cylinder compressive concrete strength
$f_{ct,sp}$	mean value of concrete splitting tensile strength
f_t	tensile strength of steel reinforcement
f_y	yield stress of steel reinforcement
k	scale factor according to EC2
k_{dg}	factor taking into account the influence of the maximum aggregate size
k_ψ	factor that depends on the deformations of the slab
m_R	average flexural strength per unit length in the support strip
m_s	moment per unit length for calculation of the flexural reinforcement in the support strip
r_s	distance between the column axis and the position of zero radial bending moment
u	length of the control perimeter
E_c	modulus of elasticity of concrete
E_s	modulus of elasticity of flexural reinforcement
V_{exp}	experimental punching load
V_{flex}	flexural capacity of slab
V_{min}	minimum value between V_{flex} and V_R
V_R	predicted punching resistance

The reduced scale specimens measured 1650 × 1650 mm^2, were 125 mm thick and intended to simulate the area near a column of an interior slab panel up to the zero moment's line (see Fig. 1).

The specimens were named based on concrete compressive strength grade (SNSC for the normal strength concrete slabs and SHSC for high strength concrete specimens) and on its longitudinal reinforcement ratio. The reinforcement ratios of specimens SHSC1, SHSC2 and SHSC3, built with HSC, were 0.94%, 1.24% and 1.48%, respectively. Specimen used as reference, SNSC, was cast with NSC and with a reinforcement ratio of 1.25%. During the manufacture of the specimens their mean effective depths (d) were measured and are presented in Table 1, where it is also presented the details of the top and bottom longitudinal reinforcements, along with its average longitudinal reinforcement ratio (ρ).

The top and bottom reinforcement layouts were orthogonal and parallel to the slab edge. The longitudinal reinforcement concrete clear cover of both faces was 20 mm.

The specimens were monotonically loaded at 0.25 kN/s rate up to failure using a hydraulic jack of 1000 kN capacity, centrally positioned under the slab. The column was simulated by means of a square steel plate with 200 mm sides and 50 mm thick. Eight points on the top of the slab were fixed to the strong floor of the laboratory using high steel strands and spreader beams according to Fig. 1.

2.1. Materials

For the NSC, locally available crushed coarse limestone aggregate was used along with medium and fine sand. For the HSC mix, crushed coarse basalt aggregates were used, together with medium and fine sand.

The HSC was produced using Portland cement type CEM I 52.5 R, while in the NSC mix was used Portland cement CEM II/B-L 32.5 N. Silica fume corresponding to 10% of the cement weight was added in the mixing process of the HSC to enhance its mechanical properties. Due to a particle size of only one hundredth of the size of the cement particles, the silica fume contributes to a denser material structure. This will effectively fill the free space between aggregates and cement particles. Furthermore, silica fume is also a pozzolanic material that reacts with the calcium hydroxide and forms cement gel which also contributes to a denser material and to increase the hardened concrete strength [14]. Because of the low water cement ratio and to improve the workability, a superplasticizer was added during the mixing of the HSC. The materials quantities used in the concrete mixtures are presented in Table 2. The maximum aggregate size is of 13.9 mm and 13.2 mm, for the HSC and the NSC, respectively.

The concrete compressive (f_c) and splitting tensile ($f_{ct,sp}$) strength were determined on 150 × 300 mm cylinders, according to EN 12390-3 [15] and EN 12390-6 [16], respectively. The

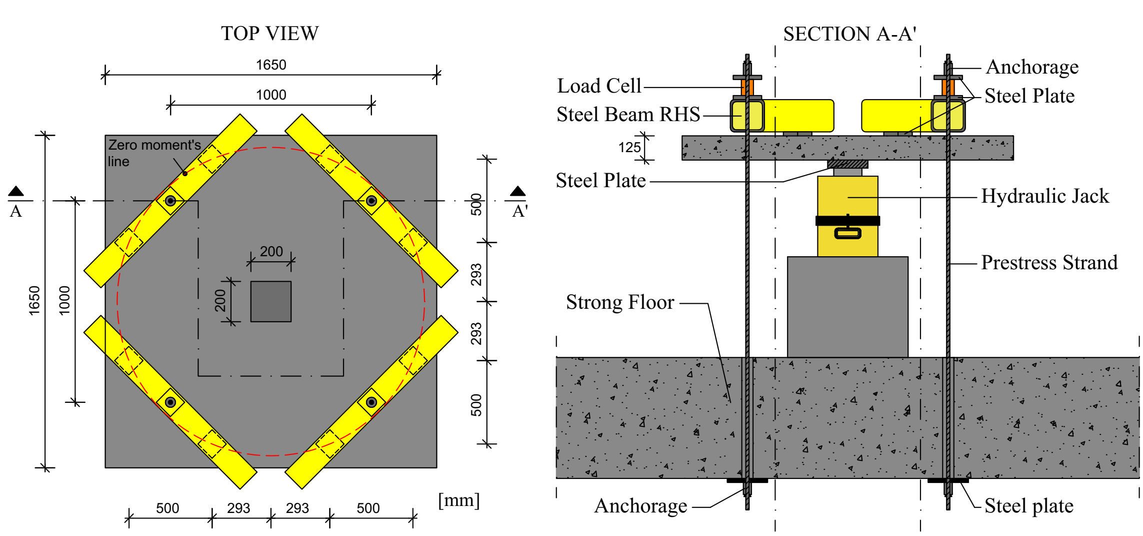

Fig. 1. Test setup.