HYBRID USE OF HPFRC IN SLAB – COLUMN CONNECTIONS UNDER CYCLIC LATERAL LOADING

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ABSTRACT
Punching shear reinforcement has already proved to be a reliable solution to improve the deformation capacity of flat slab – column connections subjected to seismic actions. Alternative approaches are becoming attractive with the development of materials such as High-Performance Fibre Reinforced Concrete (HPFRC) with better performance in tension and compression compared to conventional concrete. Motivated by the promising results obtained during an experimental campaign on hybrid HPFRC flat slabs under monotonic centred vertical loading, this paper investigates the possibility of using HPFRC to improve the behaviour of flat slabs under lateral loading (such as during earthquakes). Four reversed horizontal cyclic loading tests, under constant gravity loads, are presented. The flexural reinforcement ratio, the extent of HPFRC zone from the face of the column and the gravity load were the experimental variables considered. Results show that HPFRC can be a promising alternative to conventional punching shear reinforcement in slab column connections subjected to seismic actions, leading to increased deformation capacity. Furthermore, the results show that even a small extent of the HPFRC zone (up to 1.5 times from the face of the column) can lead to significant benefits in terms of seismic behaviour of slab – column connections, opening the possibility for an optimization of use of HPFRC.

Keywords: *flat slab; flat plate; punching; shear; HPFRC; cyclic loading; high performance fibre reinforced concrete; seismic loading; slab – column connection.*

INTRODUCTION

Flat slabs under earthquake action are prone to have a potential fragile failure due to punching. To overcome this, several solutions have been tested to enhance the punching resistance in force and deformation capacity. It is common to use stirrups or studs as punching reinforcement, solutions that have already been experimentally proven [1-5]. These solutions are efficient, but the stirrups can make the execution difficult with an introduction of additional steel elements in a zone already with a high ratio of steel reinforcement and the studs can be an expensive solution. If the dimensions of the structural elements are not a variable to consider, another solution to enhance the seismic behaviour is to improve the materials, in particular the concrete.

There have been several studies considering the use of High Strength Concrete (HSC), like [6-8], that used a concrete with a strength around 70 MPa, resulting in an improved behaviour under lateral loading. More recent tests performed by Inácio et al. [9], using a concrete with a strength around 120 MPa casted in a limited zone near the column while in the rest of the slab a normal strength concrete (NSC) was used. These tests presented a significant increase of the maximum drift reached by the specimens, from 1% in the reference specimens with NSC to 3% in the specimens with localized and limited use of HSC. The adding of fibres in the concrete is another way of improving its properties. Instead of increasing the compressive strength, it improves essentially the tension strength and the control of the cracking [10-11], that can lead to an increase even for the ultimate resistance of the reinforced concrete element. There are several studies that shows the improvement of the seismic response of flat slabs when Fibre Reinforced Concrete (FRC) is used [12-15].

The results of the two solutions presented (HSC and FRC) led to the idea of joining both into a concrete with high strength and fibre, resulting in a material named High-Performance Fibre Reinforced Concrete (HPFRC). In the study presented in this paper, flat slabs with HPFRC casted in a small area near the column were tested under horizontal cyclic actions.

EXPERIMENTAL WORK

The experimental work consisted in testing four slabs subjected to a horizontal cyclic load, under constant vertical gravity load. These slabs were built with a HPFRC near the column, to enhance the punching resistance, and NSC in the rest of the slab.

Test setup

The test setup was design and built to test flat slab specimens corresponding to mid-to-mid span in the direction of the horizontal load application (N-S) and between zero moments in the transversal direction (E-W). The boundary conditions were built using two auxiliar systems to impose equal vertical displacements and rotations in the opposite borders of the N-S direction, as shown in Figure 1. The system that applies equal displacements (coloured in blue in the figure) also applies equal vertical forces with opposite directions in the borders and the system that implies equal rotations (coloured in green in the figure) also implies equal bending moments at the borders. There is also a third system (coloured in yellow in the figure) to apply the vertical loads that follows the slab during the application of the horizontal displacement. This test setup is described in detail and discussed in several previous publications [16-17].

Summarizing, the main objective of the developed setup was to have boundary conditions in the direction of the horizontal load to allow a redistribution between positive and negative moments, resulting in a constant change of the neutral axis position in that direction during the application of the horizontal loads.

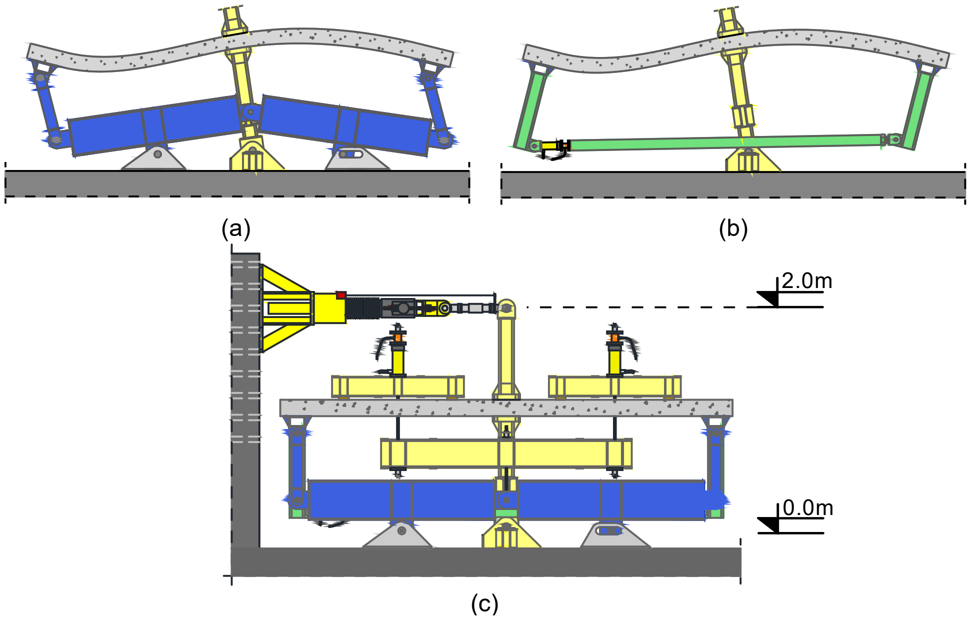

Figure 1 – Test setup a) vertical displacement and shear force compatibilization system; b) rotation and bending moment compatibilization system; c) general view

Specimens

Specimens with HPFRC

The dimensions of the slab specimens tested were 4150 mm × 1850 mm × 150 mm, corresponding the length to the N-S direction. All the specimens had an interior zone, near the column, that was casted with a High-Performance Fibre Reinforced Concrete (HPFRC). The area of that interior zone was a square with a side equal to 600 mm in 3 specimens and equal to 940 mm in the fourth slab, as illustrated in Figure 2. In the remaining part of the slab a NSC was used.

Concerning the longitudinal flexural reinforcement, two of the slabs add a low "*L*" and the other two a medium "*M*" ratio of reinforcement. This designation is consistent with previous publications [18], where 3 different reinforcement ratios were studied. The details for these reinforcements can be found in Figures 3 and 4. Table 1 complements the figure, adding the nominal average effective depth, d, and the reinforcement ratio, ρ, for each slab. The reinforcement ratio was calculated based on the top reinforcement located in a width equal to the size of the column (250 mm) plus 3d on each side of the column, in accordance with Eurocode 2 [19]. The names given to the specimens are related to the type of test (C - cyclic test), the size of zone with HPFRC and the longitudinal reinforcement ratio (L – Low or M – Medium). For example, C-HP600-M corresponds to a cyclic test, HPFRC (HP) applied in a square with a 600 mm side (600), and medium longitudinal reinforcement ratio (M). In the case of the last specimen the adding of the (g) means a specimen with a higher vertical load.

The gravity load was a variable that differed in only one of the specimens. The gravity load that was kept constant along the test was calculated to be around 53-54% of the punching resistance for three specimens and around 63% in the last tested specimen. This percentages defined as the gravity shear ratios (GSR) are also listed in Table 1, together with the applied gravity load (V_g) and the concentric punching shear resistance (V_0), calculated according with the Eurocode 2 [19] without partial factors and calculated as if the slab was made with the NSC of each slab, without HPFRC.

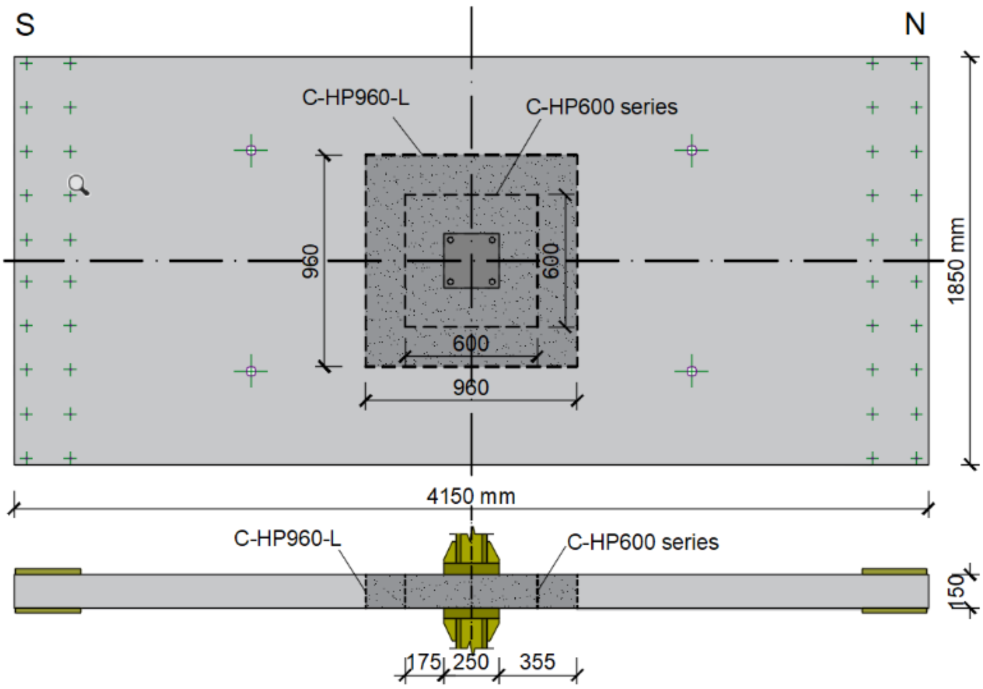

Figure 2 – Geometry of the specimens

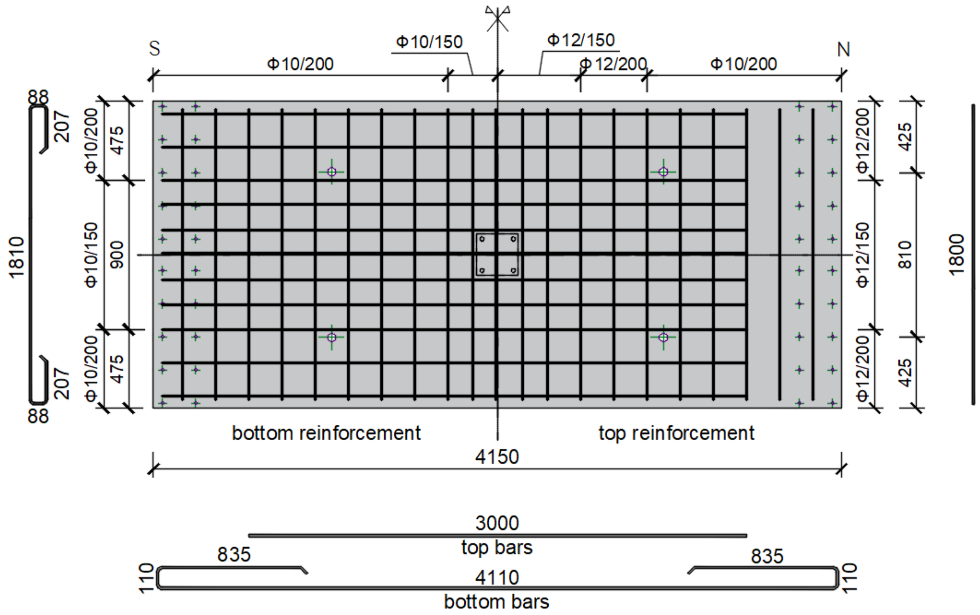

Figure 3 – "Low" reinforcement slab details

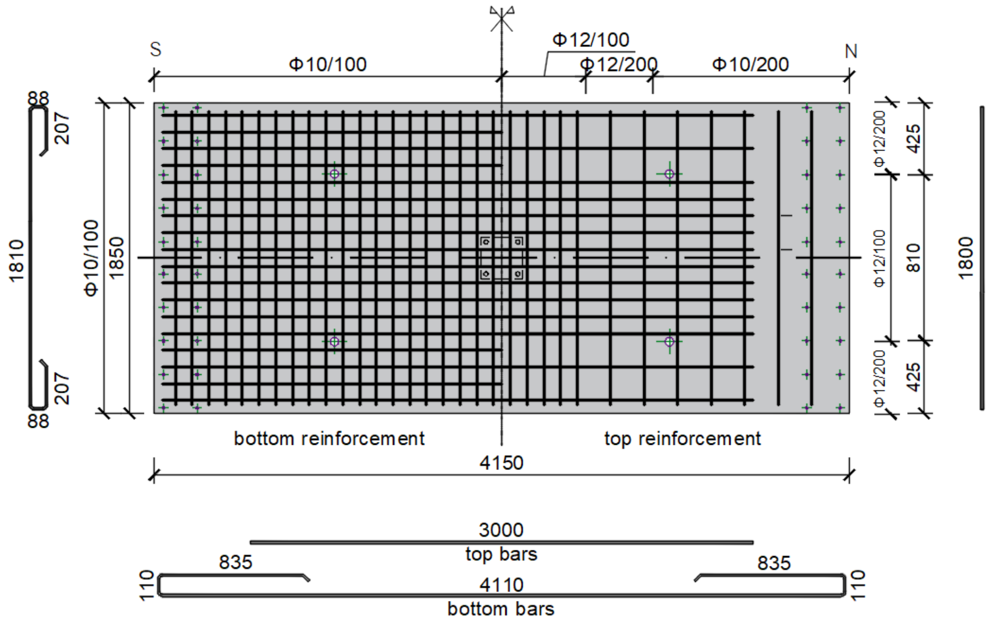

Figure 4 – "Medium" reinforcement slab details

Table 1 – Main properties of the specimens

Specimen	d (mm)	ρ (%)	V_g (kN)	V_0 (kN)	GSR = V_g/V_0
C-HP600-L	117.3	0.6	182.3	337.8	54%
C-HP960-L	117.8	0.6	178.0	333.0	53%
C-HP600-M	118.0	1.0	199.9	369.6	54%
C-HP600-M(g)	117.5	1.0	225.3	359.2	63%
C-Ref-L	117.3	0.6	165.2	284.2	58%
C50	118.0	1.0	203.4	397.9	51%

Reference specimens
In this point, the characteristics of specimens without any punching resistance enhancement method are presented to serve as reference for the results that will be presented for the specimens with HPFRC.
Two specimens will be presented, one with a “low “ ratio of longitudinal reinforcement and another with a “medium” ratio, specimens C-Ref-L [18] and C50 [16], respectively. The longitudinal reinforcements are equal to the ones presented above. The concrete used was a conventional concrete in all the slab. The reinforcement ratios and concrete compressive strength of these specimens are presented in Tables 1 and 2.

Materials

Conventional concrete
The NSC used in the slabs was an everyday mixture used in the concrete precast plant Concremat, S.A., where the slabs were built. In Table 2 the concrete strength in cubes with a side equal to 150 mm, $f_{c,cube}$, and the concrete strength in cylinders with a diameter of 150 mm and a height equal to 300 mm, f_c, are presented. These values were obtained by testing cubes and cylinders casted along with the slab, except for the specimen C-HP960-L where there were no cylinders available for testing and the values were estimated.

Table 2 – Concrete properties of the specimens

Specimen	$f_{c,cube}$ (MPa)	f_c (MPa)	$f_{c,cube\ 100,\ HP}$ (MPa)	$f_{c,HP}$ (MPa)
C-HP600-L	53.8	52.5	114.2	116.7
C-HP960-L	49.5	49.5	106.1	101.0
C-HP600-M	46.5	44.8	126.3	114.7
C-HP600-M(g)	39.1	41.9	129.9	120.1
C-Ref-L	40.1	31.3	-	-
C50	48.6	52.4	-	-

HPFRC
The HPFRC used locally on the slabs near the column was developed by Nunes et al. [20] and Blazy et al. [21]. The components and proportions used to produce the concrete can be found in Table 3. The cement used was a Portland cement with a compressive strength of 42.5 MPa at 28 days (CEM I 42.5R). The coarse aggregates used had a maximum size of 8 mm. The fibers used for this concrete were of two types, a long and a short, being the total fiber volume of 1% equally divided by both types. The long type corresponding to triple-hooked end steel fibers with a length of 60 mm, a diameter of 0.9 mm and a tensile strength of 2300 MPa. The short type corresponding to short straight fibers with a length of 13 mm, a diameter of 0.2 mm and a tensile strength of 2750 MPa.

Table 3 – Mix-design of HPFRC

Material	Quantity (kg/m^3)
Cement	531.86
Limestone powder	203.72
Silica fume	53.19
Water	147.85
Superplasticizer	12.55
Fine aggregates	811.82
Coarse aggregates	721.43
Steel fibers (long)	39.25
Steel fibers (short)	39.25

The flexural behavior of this material was characterized by Nunes et al. [20] using a three-point flexural bending test, being the stress at the limit of proportionality equal to f_L = 10 MPa and the residual flexural tensile strengths f_{R1} = 15.4 MPa, f_{R2} = 18.0 MPa, f_{R3} = 16.4 MPa and f_{R4} = 12.9 MPa, corresponding to a crack mouth opening displacement (CMOD) of 0.5 mm, 1.5 mm, 2.5 mm and 3.5 mm, respectively. The compressive strengths for the HPFRC produced for the four slabs tested are shown in Table 2, where $f_{c,cube\ 100,\ \mathrm{HP}}$ corresponds to the concrete strength in cubes with a side equal to 100 mm and $f_{c,HP}$ the concrete strength in cylinders with a diameter of 150 mm and a height equal to 300 mm. As explained for the NSC, these values were obtained by testing cubes and cylinder casted along with the slab, except for the cylinders corresponding to specimen C-HP960-L where there were no cylinders available for testing and the values were estimated.

Reinforcing steel

The longitudinal reinforcing steel used was A500NR [19]. The steel was tested, and the yield strength given from the tests was f_y = 547 MPa for the 12 mm bars and f_y = 565 MPa for the 10 mm bars.

INSTRUMENTATION

Several instruments were used to control the test and acquire the desired data. Along with the horizontal actuator, a load cell and a displacement transducer were used to measure the horizontal force and displacement. In each hydraulic cylinder used to apply the vertical load a load cell was applied. To measure the vertical displacements two lines of displacement transducers were used, one along the N-S central axis and the other in the transversal direction in the E-W central axis, as can be observed in the schematic drawing in Figure 5.

The rotations of the N-S borders were monitored using two inclinometers. To maintain those rotations equal, the forces in the strut, below the slab (see Figure 1-b) were controlled using two hydraulic cylinders and corresponding load cells. These forces are directly related to the moments applied in the N-S borders.

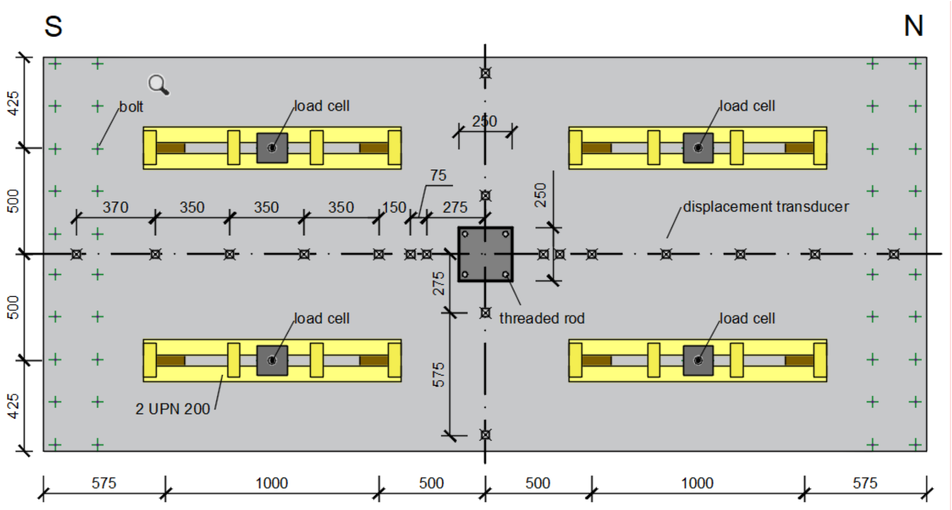

Figure 5 – Location of the vertical displacement transducers and load cells

Test protocol

The test of all specimens followed the same protocol (Figure 6). The first step was to apply the vertical load in 8 points, using four hydraulic cylinders (see Figures 1 and 5), and then the vertical load was kept constant during the rest of the test. After the vertical load application phase, cyclic horizontal displacements were applied until the end of the test. The horizontal displacements were applied in steps with increasing amplitude. For the lower amplitudes, until drifts equal to 3.5%, three repetitions of the cycles for each target displacement were applied. Then, two repetitions were applied for 4.0%. For higher drifts only one cycle was performed for each target displacement. The test ended when failure was reached or a maximum drift of 6.0%. For these cyclic tests, failure was considered to be reached when the horizontal force, after achieving its the maximum value decayed more than 20%.

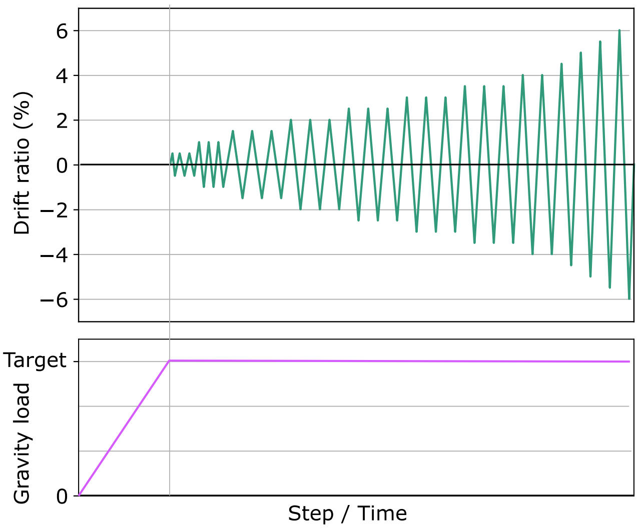

Figure 6 – Test loading protocol

RESULTS OF THE EXPERIMENTAL TESTS

Before the analysis of the results, it is important to highlight the context in which these connections are supposed to work. At the present time, the Eurocodes do not consider the flat slabs as being part of the primary resistance structure in case of an earthquake action, needing the flat slab, designed as secondary seismic structure, to withstand the horizontal deformations imposed by the earthquake action and also bearing the gravity loads. Thus, this solution must follow the structure horizontal displacement during an earthquake and the structure's horizontal resistance must be ensured by other elements, like walls or beam-column frames.

For the reasons referred above, the main result to be evaluated is the horizontal drift reached by each specimen, while sustaining the quasi-permanent vertical load. Other results, like the horizontal forces or the horizontal stiffness are also important for a structure's global analysis, but less relevant.

In Figure 7 and Table 4 the main results of the described tests are presented. It can be concluded that all the specimens with HPFRC presented a stable hysteretic cyclic response and reached high drifts, beyond values expected in a practical situation. Comparing these results with the reference specimens (C-Ref-L and C-50), that were able to reach just a maximum of 1% drift, it is clear that the studied solution resulted in a huge improvement in deformation capacity. The only specimen with HPFRC that did not reach the end of the protocol was the C-HP600-M(g), due to the higher GSR applied.

From a general point of view all the connections tested presented a very flexible behavior, with high yielding drifts for the specimens with HPFRC. The reference specimens did not reach yielding.
From these tests some comments can be made relating the reinforcement ratio. The increase in the amount of longitudinal reinforcement resulted in higher horizontal forces. In terms of horizontal displacements, the specimens with HPFRC reached the end of the protocol, conditioning the conclusions, but from previous tests higher maximum drift is expected for lower reinforcement ratios [18].

The dimensions of the area near the column with HPFRC was a parameter evaluated for the specimens with lower reinforcement ratio and the difference was that the specimen with a large area presented a higher horizontal force, what means a higher unbalanced moment, and less damage reported during the test.

Figure 8 shows the deformation pattern of the specimen C-HP960-L, where it can be seen the imposition of the boundary conditions, forcing the N-S borders to have equal vertical displacement and rotation. In

Figure 9 photos of the cracked specimens C-HP600-L and C-HP600-M near the column are shown for the final drift cycle of 6%. These photos show the degradation of the slabs and the great capacity of these slabs in sustaining the gravity loads, even for this high level of crack widths and horizontal drift applied.

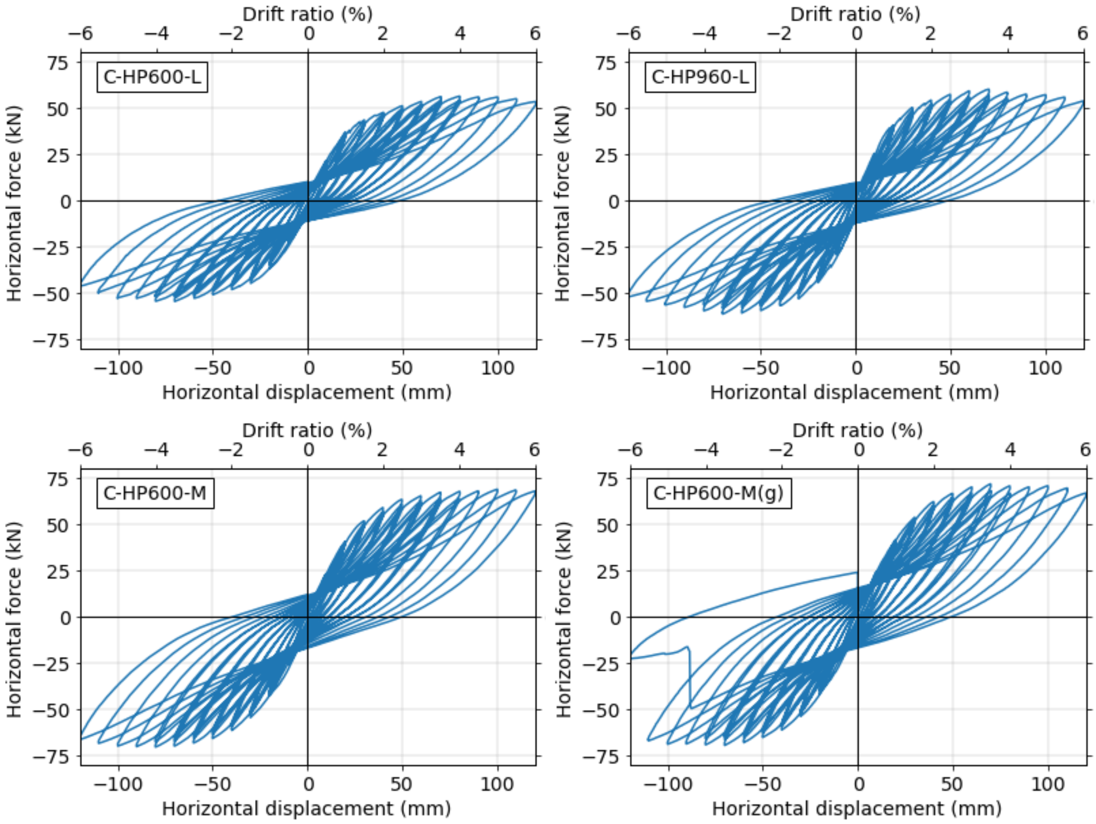

Figure 7 – Horizontal load – horizontal displacement relationship for specimens with HPFRC

Table 4 – Main properties and results for reference specimens and specimens with HPFRC

Specimen	GSR	f_c (MPa)	$d_{r,y}$ (%)	$F_{H,max}$ (kN)	$d_{r,FHmax}$ (%)	$d_{r,u}$ (%)
C-Ref-L	58%	31.3	N/A	36.4	1.5	1.0
C-HP600-L	54%	52.5	2.0	56.4	4.0	>6.0
C-HP960-L	53%	49.5	1.8	61.5	-3.5	>6.0
C-50	52%	52.4	N/A	37.4	1.1	1.0
C-HP600-M	54%	44.8	2.2	70.5	-4.0	>6.0
C-HP600-M(g)	63%	41.9	2.1	71.9	3.5	5.5

N/A = not applicable.

Figure 8 – Photo taken during the test of specimen C-HP960-L during a 6% drift cycle

Figure 9 – Photos of C-HP600-L (left) and C-HP600-M (right) taken during a 6% drift cycle

CONCLUSIONS

In this paper, four specimens of flat slabs using a hybrid solution HPFRC/NSC, being the HPFRC only used in a localized area near the column, were tested and compared with two reference specimens made entirely of NSC. In the specimens with HPFRC, three parameters were changed, the area of the HPFRC, the amount of longitudinal reinforcement and the GSR. The specimens were subjected to cyclic horizontal displacements while sustaining constant vertical gravity loads.

The tested specimens with HPFRC presented a stable hysteretic response, achieving high horizontal drifts. Comparing the solutions with HPFRC to the reference specimens, there was a huge increment in the attained drifts. The reference specimens only achieved 1.0% drift while specimens with HPFRC and about 53-54% of GSR went to the end of the loading protocol for a 6.0% drift. Increasing the GSR to about 63% resulted in a slightly decrease of deformation capacity, achieving a maximum drift of 5.5%. The horizontal strength (or unbalanced moment) also increased with the use of HPFRC. There was no considerable difference in for this output when the vertical load (GSR) was increased.

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