# Seismic behaviour of slab – column connections with various punching shear enhancement methods

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## Abstract

A series of slab-column connection specimens have been tested under reversed horizontal cyclic loading and constant gravity loads during the last years at NOVA School of Science and Technology. These specimens have been tested under similar loading conditions, using a test setup that simulates slab continuity in the longitudinal direction, the same overall dimensions (4.15m × 1.85m × 0.15m) and approximately the same flexural reinforcement ratio of 1%. Various punching shear enhancement methods have been tested, including stirrups, headed studs, fibre-reinforced concrete, high-strength concrete and post-installed bolts. This paper presents a summary of the reported tests and a comparison of the main results, with the purpose of comparing various punching shear enhancement methods for seismic loading conditions. The results from different experimental campaigns are compared. It is shown that relatively large drift ratios at failure are achieved by employing punching shear reinforcement in the form of stirrups or headed studs. However, less conventional methods such as fibre reinforced concrete and high strength concrete are shown to be promising alternatives. Compared to the reference specimens (without any punching shear reinforcement or other enhancement) that failed at 1% horizontal drift, the other specimens failed for significantly higher drifts, ranging from 2.5% to above 6.0%.

***Keywords:*** *cyclic loading, seismic, flat slab, punching shear reinforcement, advanced concrete materials.*

## 1. Introduction

Flat slabs are used worldwide in residential and office Reinforced Concrete (RC) buildings. Traditionally, flat slabs have been designed to carry gravity loads, but there has been an ever increasing demand from the construction industry to use flat slabs in earthquake prone buildings, due to their numerous advantages in terms of cost and convenience in designing the interior space.

Active research on the seismic behaviour of slab-column connections originated in the 1970s with works from research teams at the University of Washington (Hanna et al., 1975; Hawkins et al., 1974) and University of Canterbury (Islam and Park, 1976). It soon became apparent that, as it was previously observed for gravity loading, the risk of punching shear failures under lateral loading can be mitigated by employing punching shear reinforcement. Since then, numerous techniques have been developed to enhance the deformation capacity of slab-column connections and therefore ensure their safety while undergoing lateral displacements imposed by the primary seismic load resisting system during an earthquake.

Headed shear studs have been shown to be one of the most practical and effective solutions for lateral loading (Brown, 2003; Dilger and Cao, 1994; Robertson et al. 2002). Properly detailed stirrups can significantly enhance the performance of slab-column connections under lateral loading (Hanna et al., 1975; Hawkins et al., 1974; Islam and Park, 1976; Robertson et al., 2002). Other reinforcement systems such as lattice reinforcement (Kang et al., 2013; Park et al., 2007), thin-plate stirrups (Kang and Wallace, 2008), bent-up bars (Islam and Park, 1976; Robertson and Johnson, 2006), post-installed bolts (Ramos, et al., 2000; Almeida et al., 2020b; Bu and Polak, 2009; Topuzi et al., 2017) have also been investigated in slab–column connections under lateral loading.

Attempts to use advanced concrete materials such as Fibre Reinforced Concrete (FRC) and High-Strength Concrete (HSC) as an alternative to traditional punching shear reinforcement systems in flat slabs subjected to lateral loading have produced promising results. Tests on HSC specimens under lateral loading have been reported in several publications (Emam et al., 1997; Inácio et al., 2020a; Marzouk et al., 2001), whereas FRC has been used in some publications (Cheng et al., 2010; Durrani and Diaz, 1992; Schreiber and Alexander, 2001).

A series of reversed horizontal cyclic loading tests have been conducted during the last several years at NOVA School of Science and Technology. The work started with the development of an innovative test setup that simulates flat slab continuity in the direction of loading with the purpose of ensuring more realistic conditions compared to previous tests. The first tests were conducted on specimens without punching shear reinforcement, with varying gravity load (Almeida et al., 2016). Subsequently, tests on specimens reinforced with headed studs (Isufi et al., 2019; 2020), stirrups (Almeida et al., 2020a), HSC (Inácio et al., 2020a) and FRC (Gouveia et al., 2019) and strengthening with post-installed bolts (Almeida et al., 2020b) were conducted. All the specimens presented in the aforementioned tests had similar geometry, flexural reinforcement detailing and quantity as well as a comparable ratio between the applied gravity load and the concentric punching shear resistance (Gravity Shear Ratio – GSR). In this context, this paper summarizes the main findings from each of the aforementioned publications and provides a direct comparison of the different punching shear enhancement methods for seismic loading conditions.

## 2. Geometry, test setup and instrumentation

The specimens had the same nominal geometry and flexural reinforcement, as illustrated in Figure 1. The overall dimensions of the specimens were 4150 mm × 1850 mm × 150 mm.

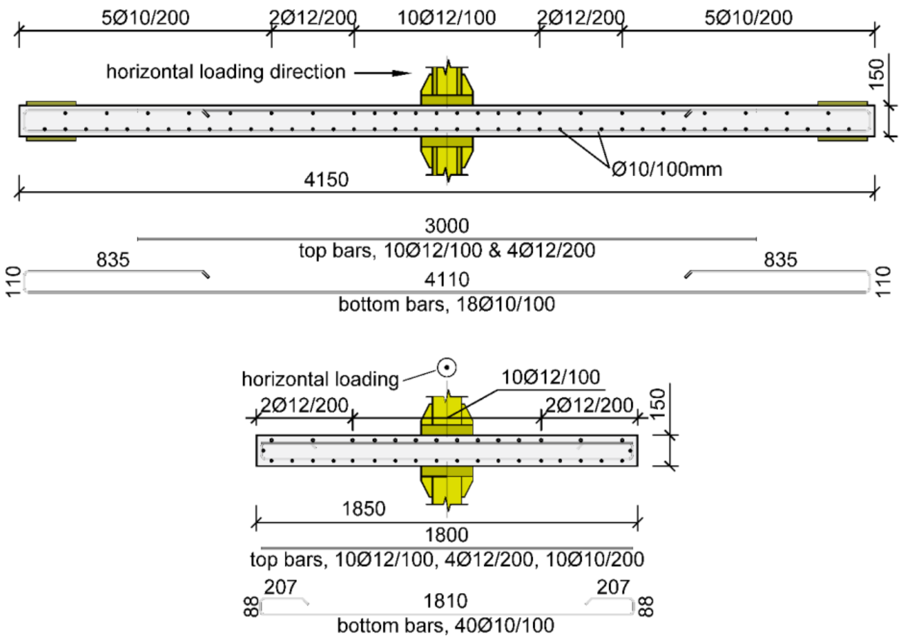
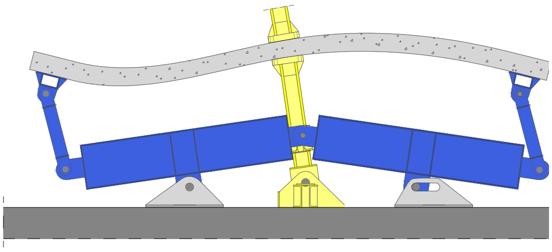
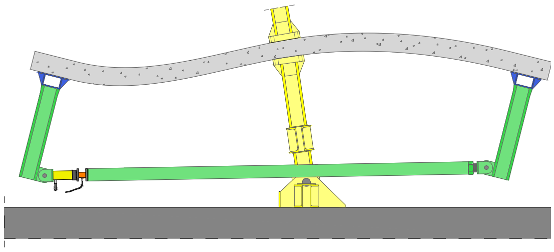



Figure 1 – Flexural reinforcement details

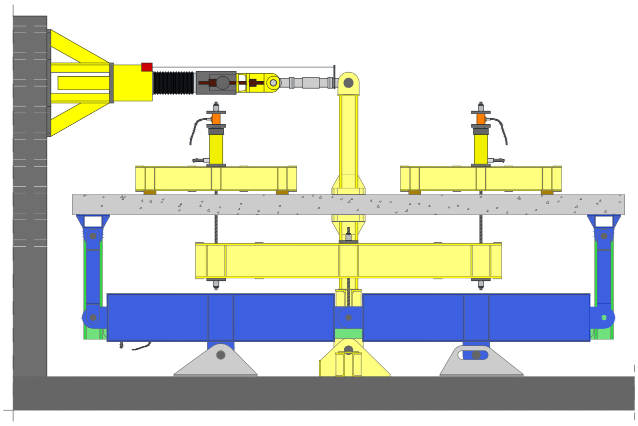
The test setup allows vertical displacements at the opposite slab borders and it ensures equal magnitude shear forces, bending moments and rotations at the slab edges as well as mobility of the line of inflection location along the longitudinal direction. For vertical loads, the shear forces and rotations at the opposite borders are zero and the vertical displacements and the bending moments are the same at the opposite longitudinal borders. For horizontal actions, the vertical displacements and shear forces are equal in magnitude, but with opposite signs. The test setup is seen in action under horizontal loading conditions in Figure 2-a,b. A general view is given in Figure 2-c. Detailed description of the test setup is provided in other publications (Almeida et al., 2016; Ramos et al., 2017).



(a)



(b)



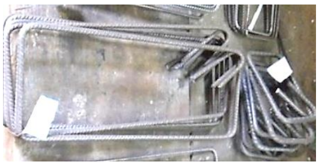
(c)

Figure 2 – Test setup a) vertical displacement and shear force compatibilization system under slab's vertical and horizontal deformation; b) rotation and bending moment compatibilization system under slab's vertical and horizontal deformation; c) general view (Ramos et al., 2017)

## 3. Punching shear enhancement methods

Five punching shear enhancement methods have been tested so far using the test setup of Figure 2: a) headed studs; b) stirrups; c) post-installed bolts; d) HSC; e) FRC, as illustrated in Figure 3.

(a)



(b)

(c)

(d)

(e)

Figure 3 – Punching shear enhancement methods tested: a) headed studs; b) stirrups; c) post-installed bolts; d) High strength concrete in vicinity of the column; e) steel fibers.

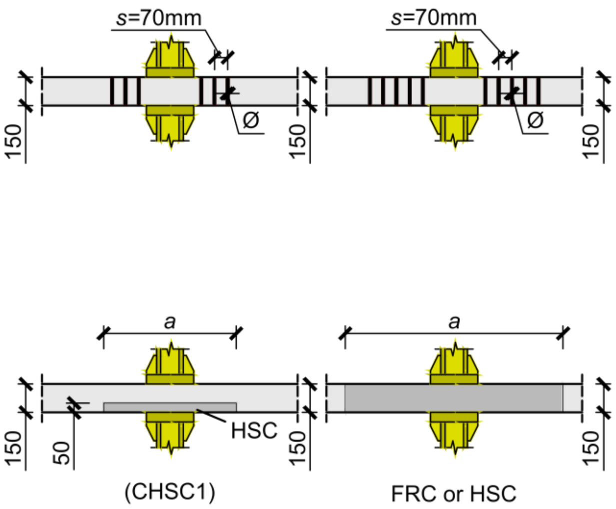
Headed studs made of 8 mm diameter deformed bars welded into steel plates (Figure 3-a) were used by Isufi et al. (2019, 2020) in four specimens with similar layout but with different number of rows of shear reinforcement legs. In one specimen (C-SSR3), only three rows of shear reinforcement were used, whereas the other three specimens had five rows of studs. The three specimens with five rows of studs differed from one another by the magnitude of the gravity load.

Almeida et al. (2020a) tested four specimens reinforced with stirrups around the column. Two shear reinforcement ratios were tested: one was achieved by using 16 vertical legs of diameter 4.5 mm per perimeter and the higher ratio was achieved by using 8 legs of diameter 6 mm and 8 other legs of diameter 8 mm. The higher shear reinforcement ratio corresponded to almost the same total amount of shear reinforcement as that provided in Isufi et al. (2019, 2020) through studs. For each shear reinforcement ratio, a layout with 3 and another with 5 perimeters of vertical shear reinforcement legs were tested.

Three reversed horizontal cyclic loading tests with hybrid use of HSC in the vicinity of the column were reported in Inácio et al. (2020a). In one of the specimens, HSC was applied only through the bottom 50 mm of the slab, whereas in the two other specimens HSC was applied throughout the entire depth of the slab. For all the specimens, the region with HSC was limited to only a square with side length equal to 700 mm, 1150 mm and 850 mm, for specimen CHSC1, CHSC2 and CHSC3 respectively.

Gouveia et al. (2019) reported four reversed horizontal cyclic loading tests on specimens with steel FRC in the vicinity of the column. The specimens differed by the fiber volume fraction and the type of fibers that were used. Another variable was the extent of the zone with FRC: in the specimen with 1% fiber volume fraction and fibers of type 3D (specimen named F1.0_3D) the FRC region was a square with side dimension 700 mm, whereas a side dimension of 900 mm was used for the other specimens. The residual flexural tensile strengths $f_{R,1}$ and $f_{R,3}$ were 4.84 MPa and 3.67 MPa respectively for F0.5_4D, 6.83 MPa and 5.93 MPa for F0.75_4D and 10.49 and 9.63 for F1.0_4D ($f_{R,1}$ and $f_{R,3}$ are not available for F1.0_3D) (Gouveia 2017).

Almeida et al. (2020b) tested two specimens strengthened with post-installed bolts in two arrangements: radial and cruciform. Three perimeters of twelve M10 bolts were used. Details of the shear reinforcement for all the above-mentioned specimens are summarized in Figure 4. Complementary information is provided in Table 1.




| Specimen | Reference | Type | Ø mm | rows |
|---|---|---|---|---|
| C-SSR3 | Isufi et al 2019 | studs | 8 | 3 |
| C-SSR5a to c | Isufi et al 2019 | studs | 8 | 5 |
| C-50 STR1 | Almeida et al 2020 | stirrup | 4.5 | 3 |
| C-50 STR2 | Almeida et al 2020 | stirrup | 6&8 | 3 |
| C-50 STR3 | Almeida et al 2020 | stirrup | 4.5 | 5 |
| C-50 STR4 | Almeida et al 2020 | stirrup | 6&8 | 5 |
| C-50 BR&BC | Almeida et al 2020 | bolts | 10 | 3 |

| Specimen | Reference | Type | *a* (mm) |
|---|---|---|---|
| CHSC1 | Inácio et al 2020 | HSC | 700 |
| CHSC2 | Inácio et al 2020 | HSC | 1150 |
| CHSC3 | Inácio et al 2020 | HSC | 850 |
| F0.5-4D | Gouveia 2019 | FRC | 900 |
| F0.75-4D | Gouveia 2019 | FRC | 900 |
| F1.0_4D | Gouveia 2019 | FRC | 900 |
| F1.0_3D | Gouveia 2019 | FRC | 700 |

Figure 4 – Description of shear reinforcement or HSC/FRC geometry used in the specimens

## 4. Results and discussion

Although the ultimate drift capacity varied from specimen to specimen, the behaviour of the specimens was rather similar, with pinched hysteresis loops. A typical horizontal force – displacement relationship is shown in Figure 5, where symbols $P_{max}$ (maximum horizontal force) and $d_u$ (ultimate drift) are defined. The ultimate drift is taken as that corresponding to the maximum drift cycle the specimen was able to complete before failure (with failure defined by a drop by more than 20% of the horizontal load after peak has been reached). Results for each slab – column connection are presented in Figure 6.

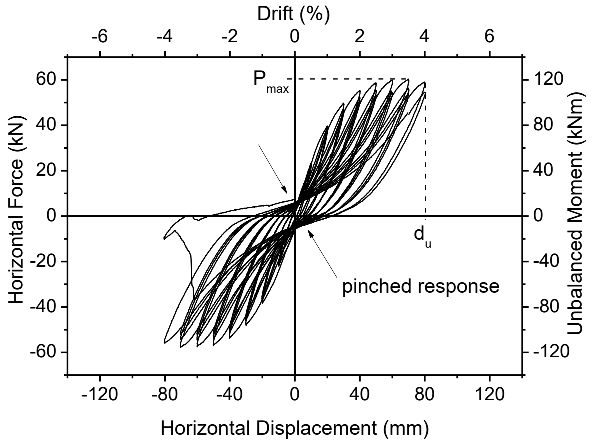



Figure 5 – Typical result (specimen C-SSR3 from Isufi et al. 2019)

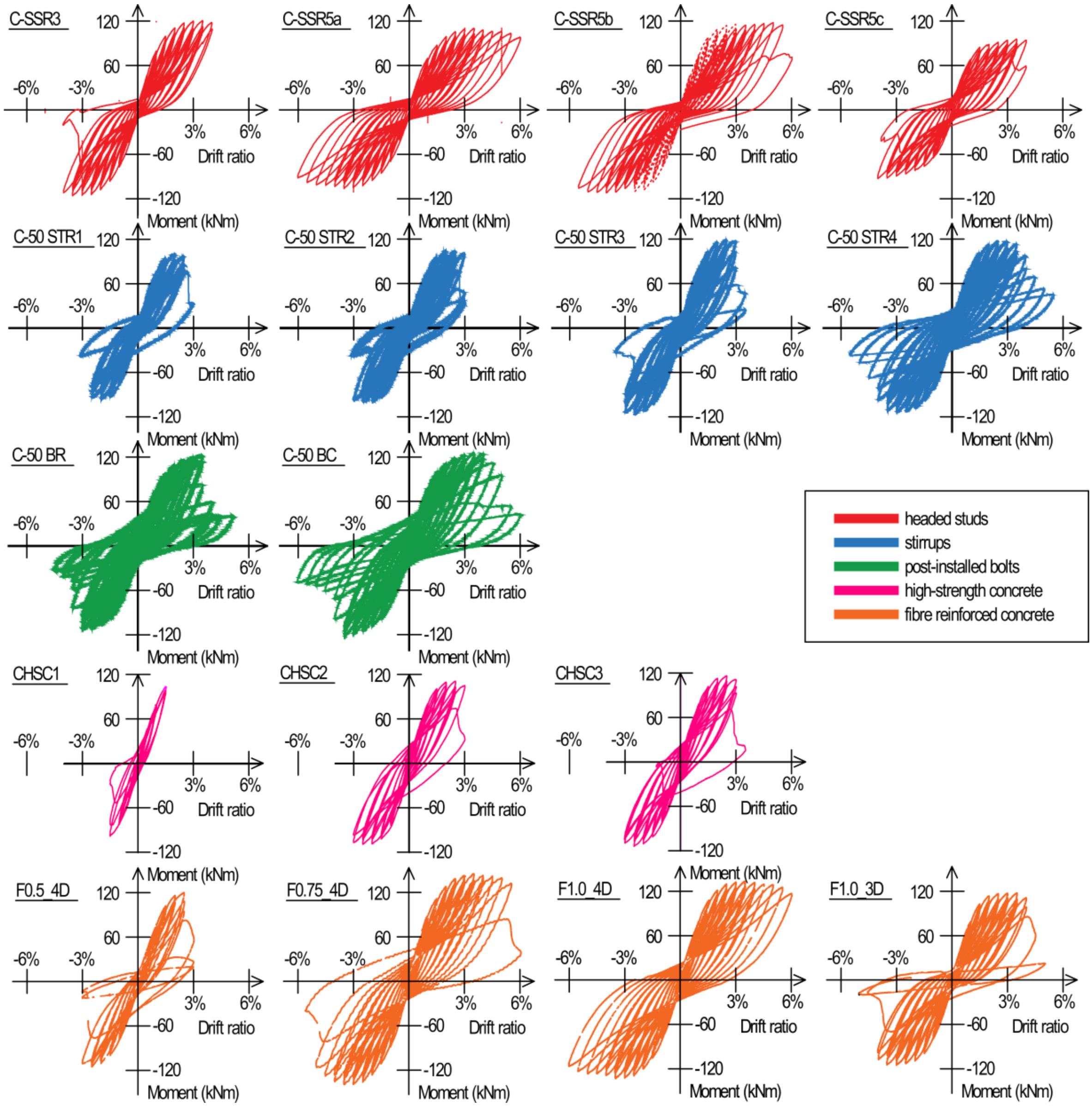



Figure 6 – Unbalanced moment – drift relationships for all specimens with shear reinforcement, HSC and FRC

All specimens except C-50 BR, C-50 BC, CHSC1 and F0.5_4D reached a clear horizontal plateau in the force – displacement relationship, indicating that the respective employed punching shear enhancement methods were effective in promoting flexural failures over brittle shear failures (Figure 6).

The ultimate drifts are summarized in Table 1. The table contains also the compressive strength determined from 150 × 300 mm cylinders ($f_c$), the applied gravity load ($V_g$) and the maximum horizontal force attained by the specimens during the test ($P_{max}$, see also Figure 5). The table shows that the ultimate drift ratios were significantly higher compared to those of the reference specimens C-50 and C-Ref without punching shear reinforcement, with normal strength concrete (NSC), that were tested in Almeida et al. (2016) and Isufi et al. (2019). These reference specimens failed for a drift ratio of only 1%, in a brittle manner, prior to developing their unbalanced moment transfer capacity through flexure.

A displacement ductility factor was calculated for all the specimens that reached a horizontal plateau and the results are summarized in Figure 7 and Table 1. The ductility factor was calculated as the ratio between the ultimate drift ratio (Table 1) and the yield drift estimated from a bilinear approximation of the experimental backbone curves for positive drifts up to the point with peak unbalanced moment. Figure 7 and Table 1 indicate that the secant stiffness to yielding point of the specimens was comparable, i.e. it is not significantly affected by the punching shear system. The yielding drifts for all specimens ranged between approximately 1.3% and 2.0% (Table 1). These yielding drifts are relatively high (comparable to design drifts for typical buildings under moderate seismicity). This behaviour is the result of high flexibility of slab – column connections in general, which cannot be mitigated by simply enhancing the punching shear capacity. The ductility factors in Figure 7 and Table 1 are relatively low, starting from around 1.8. For the specimens that did not fail in punching, the available ductility factor exceeds 3 (the exact value cannot be calculated because failure did not occur until the end of the test). Nonetheless, due to the high flexibility and high yielding drifts, a high available ductility factor is not necessary for slab – column connections in buildings where inter-storey drifts are controlled by another load resisting system (such as shear walls), as also discussed earlier in Pan and Moehle (1989).

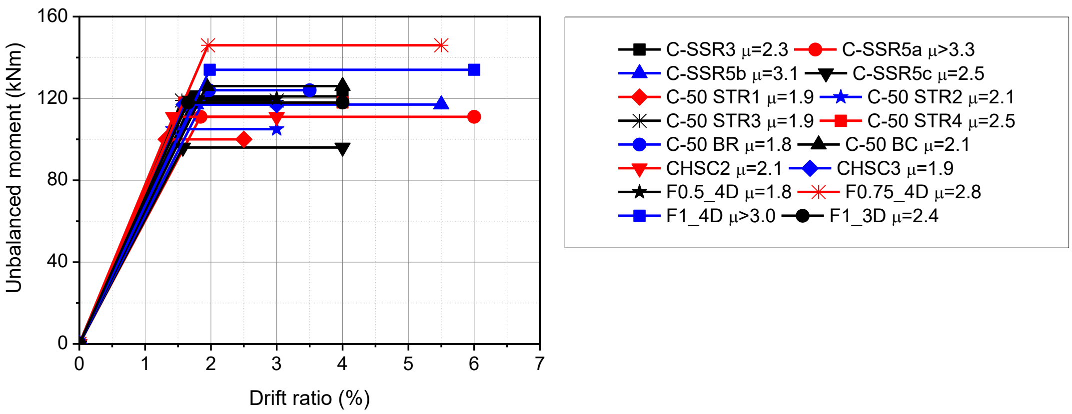



Figure 7 – Bilinear approximations and displacement ductility factors

Figure 8 compares the behaviour of the two reference specimens: C-Ref published in Isufi et al. (2019) and C-50 from Almeida et al. (2016). The figure shows that the two test results were similar. The maximum horizontal force (and unbalanced moment) was slightly larger in C-50. A possible explanation for this is the fact that the applied gravity load was slightly smaller in this specimen. The figure shows also that the loading and unloading stiffness, as well as the area enclosed by the hysteresis loops are almost identical in both specimens.

Among the specimens shown in Table 1, it is noted that the highest drift ratio was attained in specimens with five perimeters of studs and low gravity load (C-SSR5a) and the specimen with steel fiber reinforced concrete with fiber volume ratio 1% and fiber type 4D (specimen F1.0_4D). These two specimens did not fail in punching until the end of the protocol (at 6%, see also Figure 6).

The original purpose of the tests was not to attain the highest drift ratio among various solutions, therefore the amount of shear reinforcement and extent of zone with FRC or HSC varied from specimen to specimen and not all specimens are comparable. The results, nonetheless, indicate that a slightly higher drift capacity was achieved through studs compared to stirrups when comparing similar specimens (for example, specimen C-SSR3 and specimen C-50 STR2 or specimens C-SSR5b and C-50 STR4 with approximately the same quantity of shear reinforcement). Looking at specimens with HSC, it is noticed that drift ratios comparable to those attained in shear reinforced specimens can be achieved when HSC is used throughout the entire depth of the specimen in a limited region around the column. The specimen with HSC limited to the lower 50 mm of the slab sustained drifts only slightly higher than the reference specimens C-50 and C-Ref (Almeida et al., 2016; Isufi et al., 2019). Earlier works (Inácio et al., 2020b) have shown that this solution (with HSC only over a limited depth) works well for gravity loading.

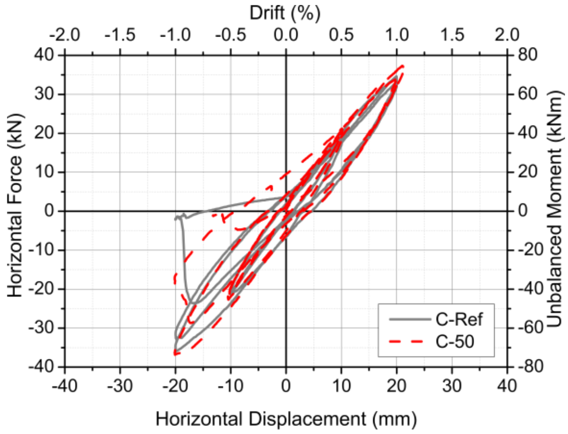



Figure 8 – Comparison of specimens without shear reinforcement, with conventional normal strength concrete

Table 1 – Description of the specimens and main results

| **Specimen** | **Reference** | **Type** | **$f_c$*** | **$V_g$** | **$P_{max}$** | **$d_y$** | **$d_u$** | **$\mu=d_y/d_u$** |
|---|---|---|---|---|---|---|---|---|
| | | | **(MPa)** | **(kN)** | **(kN)** | **(%)** | **(%)** | |
| C-50 | Almeida et al., (2016) | none | 52.4 | 203 | 37.4 | - | 1.0 | - |
| C-Ref | Isufi et al., (2019) | none | 62.3 | 225 | 36.0 | - | 1.0 | - |
| C-SSR3 | | studs | 41.2 | 196 | 60.4 | 1.7 | 4.0 | 2.3 |
| C-SSR5a | | studs | 27.0 | 169 | 55.2 | 1.8 | 6.0** | >3.3 |
| C-SSR5b | | studs | 57.6 | 214 | 58.9 | 1.8 | 5.5 | 3.1 |
| C-SSR5c | | studs | 69.9 | 275 | 47.9 | 1.6 | 4.0 | 2.5 |
| C-50 STR1 | Almeida et al., (2020a) | stirrups | 53.1 | 210 | 49.5 | 1.3 | 2.5 | 1.9 |
| C-50 STR2 | | stirrups | 52.5 | 216 | 52.0 | 1.4 | 3.0 | 2.1 |
| C-50 STR3 | | stirrups | 49.2 | 202 | 59.3 | 1.6 | 3.0 | 1.9 |
| C-50 STR4 | | stirrups | 44.4 | 196 | 58.4 | 1.6 | 4.0 | 2.5 |
| C-50 BR | Almeida, et al.., (2020b) | bolts | 57.6 | 220 | 61.0 | 2.0 | 3.5 | 1.8 |
| C-50 BC | | bolts | 58.8 | 222 | 62.2 | 1.9 | 4.0 | 2.1 |
| CHSC1 | Inácio et al., (2020a) | HSC | 61.6 (115.2) | 222 | 52.3 | - | 1.5 | - |
| CHSC2 | | HSC | 45.9 (120.2) | 200 | 55.8 | 1.4 | 3.0 | 2.1 |
| CHSC3 | | HSC | 48.9 (123.6) | 213 | 58.4 | 1.6 | 3.0 | 1.9 |
| F0.5_4D | Gouveia et al., (2019) | FRC | 44.3 (56.6) | 196 | 59.5 | 1.7 | 3.0 | 1.8 |
| F0.75_4D | | FRC | 39.2 (65.0) | 194 | 72.8 | 2.0 | 5.5 | 2.8 |
| F1.0_4D | | FRC | 52.3 (57.9) | 208 | 66.7 | 2.0 | 6.0** | >3.0 |
| F1.0_3D | | FRC | 42.4 (52.3) | 192 | 58.8 | 1.7 | 4.0 | 2.4 |

* values inside brackets correspond to HSC or FRC; ** specimen did not fail until the end of the test

## 5. Conclusions

The main conclusions from a series of tests on flat slabs subjected to combined gravity loads and reversed horizontal cyclic displacements were discussed in this paper. The specimens were similar in terms of geometry, flexural reinforcement and loading conditions, but different punching shear enhancement methods were used, including conventional shear reinforcement (stirrups, studs, post-installed bolts) as well as high strength concrete and fibre reinforced concrete in the vicinity of the column.

Regardless of the enhancement method employed, the behaviour was characterized by pinched hysteresis loops and relatively high yielding drifts, indicating a low energy dissipation capacity and low secant stiffness of the slab-column connections. The ultimate drift capacity, however, was significantly enhanced compared to reference specimens with conventional concrete and no shear reinforcement.

It is shown that the employment of the tested enhancement methods can promote flexural failure mode and prevent or sufficiently postpone brittle failure (punching shear failure). Even a very small amount of punching shear reinforcement, such as the case of specimen C-50 STR1 with 4.5 mm stirrups, can lead to a significant enhancement of the drift capacity of slab-column connections. Comparing different enhancement methods, it is noticed that headed studs lead to a slightly higher drift capacity compared to stirrups for the tested conditions. The results show that advanced concrete materials such as high strength concrete and fibre reinforced concrete are promising alternatives to conventional shear reinforcement in seismic loading conditions. For flat slabs initially designed without punching shear reinforcement, post-installed bolts were shown to be an easy and effective strengthening solution resulting in a behaviour comparable with that of flat slabs with internal punching shear reinforcement.

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