Reinforced concrete flat slab with opening under lateral loading

Massimo Lapi[a], Antonio Pinho Ramos[b], Maurizio Orlando[a], Paolo Spinelli[a]
[a] *Dipartimento di Ingegneria Civile e Ambientale, Via di S. Marta, 50139 Firenze, Italy*
[b] *CERIS, Faculdade de Ciências e Tecnologia, Universidade NOVA de Lisboa, Portugal*

Keywords: Punching of R/C flat slab; seismic behaviour; opening close to the column;

ABSTRACT
Reinforced concrete flat-slabs have been extensively used in the last decades thanks to shorter construction time and minimal structural depth. However, under gravity loading the reduced thickness provides high stresses in proximity of columns that could induce the punching failure of the flat-slab. Furthermore, for combined gravity and lateral loading the slab-column joint exhibits a very brittle behaviour against horizontal drift due to premature failure caused by punching. This paper deals with the behaviour of slab-column connections in presence of an opening close to the column, under combined gravity and seismic loading. In a previous work the authors presented the preliminary results of a new experimental campaign characterized by different positions of the opening with respect to the direction of the seismic loading. In this paper those results are discussed and compared with results achieved without opening. Tests were performed at the structural laboratory of New Lisbon University. Results show how the presence of the opening provide a detrimental effect in the response of the slab-column connection under vertical loading, while under seismic actions the presence of the opening is less affecting the slab response.

1 INTRODUCTION

Punching of R/C flat slabs is a very brittle failure that could bring to the progressive collapse of the entire building with limited warning signs (Lapi et al. 2017). This phenomenon is very complex and it is affected by several variables like concrete compressive strength, longitudinal reinforcement ratio, effective depth, slab slenderness and support size. In presence of eccentric loading this phenomenon becomes even more complex and it prevision results very difficult. Despite the several studies performed in the last years the determination of the punching strength in presence of unbalanced moment is still affected by uncertainties.

The models developed in the last decades are far to be considered comprehensive. Di Stasio and Van Buren introduced the eccentricity of shear (Di Stasio and Van Buren 1960), assuming a linear distribution of shear stress. Later Moe suggested that the eccentricity of shear contributes to one third of the entire unbalanced moment (Moe 1961). In 1968 Hanson and Hanson stated that the portion of unbalanced moment transferred by eccentricity of shear is equal to 0.4 (Hanson and Hanson 1968). Since 1971 the ACI provisions for punching shear are grounded on this approach. Despite these evidence, Mast stated that the elastic distribution of shear stress due to a moment acting between a slab and a column is close to be rectangular (Mast 1970). Starting from this hypothesis and assuming the interaction curve developed by Stamenkovic and Champman (Stamenkovic and Chapman 1974) Regan developed the punching provision for Model Code 1990 (CEB/FIP 1993).

However these researches were focused on static problems where the unbalanced moment is provided by an eccentric vertical loading. The first research dealing with seismic behaviour of slab-column connections is due to Hawkins et al. that showed the beneficial effects provided by shear reinforcement (Hawkins et al. 1975). Later Pan and Moehle highlighted the significant effects of gravity load on the ultimate drift capacity of the slab column connection subjected to combined vertical and horizontal loading (Pan and Moehle 1989).

In 2000 Megally and Ghali provided a procedure for design slab-column connections in order to avoid premature punching failure (Megally and Ghali 2000). This procedure represents the background to ACI 421.2R-10 (ACI-ASCE Committee 421 2010) and it is also the reference of ACI 318-14 (ACI Committee 318 2014). In 2009 Broms proposed a new mechanical model for transfer of unbalanced moment caused by imposed rotation of the slab-column connection (Broms 2009). Recently Drakatos et al. developed an analytical model based on the Critical Shear Crack Theory (CSCT) specifically thought for slab-column connections under seismically induced deformations (Drakatos et al. 2018).

The present work deals with the behaviour of slab-column connection under vertical and horizontal loading in presence of opening adjacent to the column. Experimental results dealing with this topic are very scarce. El-Salakawy et al. (El-Salakawy et al. 1999) investigated edge connections with opening adjacent to the column, under monotonic lateral loading.

Recently, Lapi et al. performed an experimental campaign dealing with the seismic behaviour of slab with opening (Lapi et al. 2019). In this paper these results are discussed and compared with those achieved by Almeida et al. (Almeida et al. 2016) (Almeida et al. 2019) for slabs without opening. In the following the experimental campaign is briefly shown then the analysis of the results is provided.

2 EXPERIMENTAL CAMPAIGN

2.1 *Test setup*

The experimental campaign performed by Lapi et al. (Lapi et al. 2019) was hold at the New Lisbon University using the test setup developed by Almeida et al. (Almeida et al. 2016). The latter represents and attempt to overcome the limitations of isolated specimens caused by simplified border conditions. The test setup allows equal vertical displacements and rotations at the borders in longitudinal direction. The compliance of equal vertical displacement at the borders is allowed by a see-saw system (Figure 1, blue system) while the compliance of equal rotations is provided by two pinned frames connected to the borders by vertical columns (Figure 1, green system). The vertical load is provided by means eight points on the top of the slab, the contrast is guaranteed by a closed structure that provides the vertical force to the 250x250 mm steel column (Figure 1, yellow system). The horizontal load is provided by the actuator through two halves steel columns.

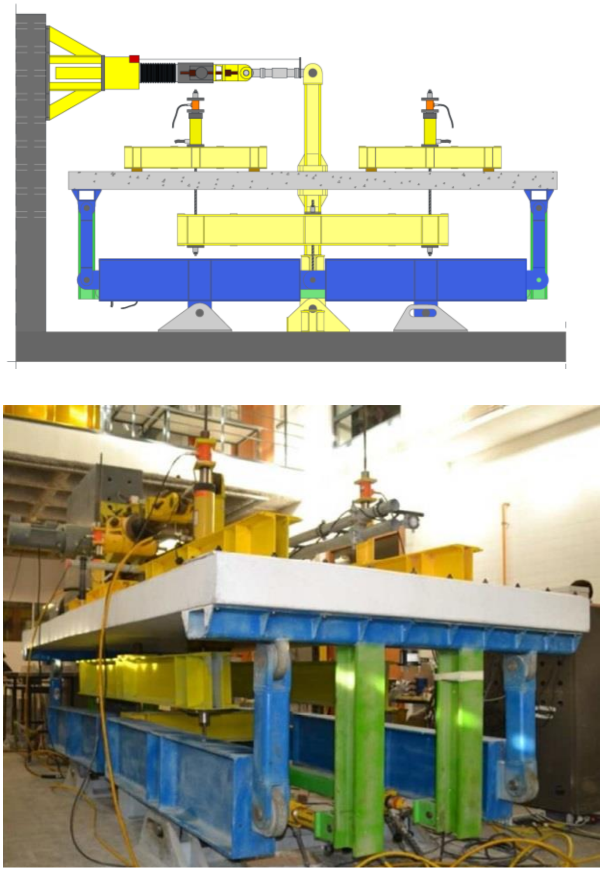

Figure 1. Setup at the New Lisbon University.

2.2 *Specimens and materials*

The specimens are 4150 x 1850 x 150 mm, the N-S borders represent the mid-span lines while the E-W borders represent the 22% of the span length (Figure 2).

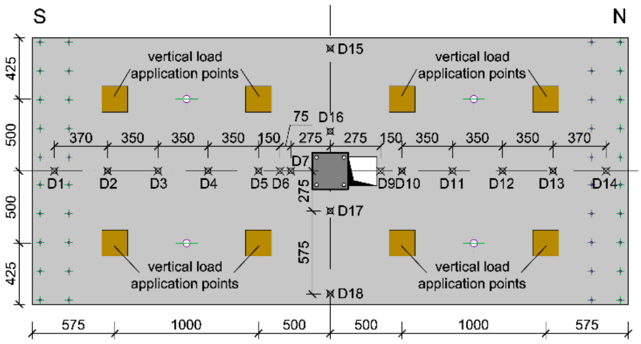

Figure 2. Specimen dimensions.

The 200 x 200 mm opening is placed adjacent to the column in north direction. The clear cover was 20 mm, the effective depths resulted 118 mm and 120 mm for top and bottom reinforcement respectively. The top longitudinal reinforcement ratio at the column is about 1%. The higher effective depth is oriented in N-S direction. Vertical displacements were monitored by means of 17 LVDTs placed on the top of the slab while the horizontal displacement was monitored by means one LVDT placed on the top of the steel column.

3 EXPERIMENTAL RESULTS

3.1 SO1-01

The first specimen was tested under vertical loading only therefore the horizontal actuator was not connected to the column to avoid accidental transfer of unbalanced moment. The punching capacity resulted about 300 kN (Figure 3).

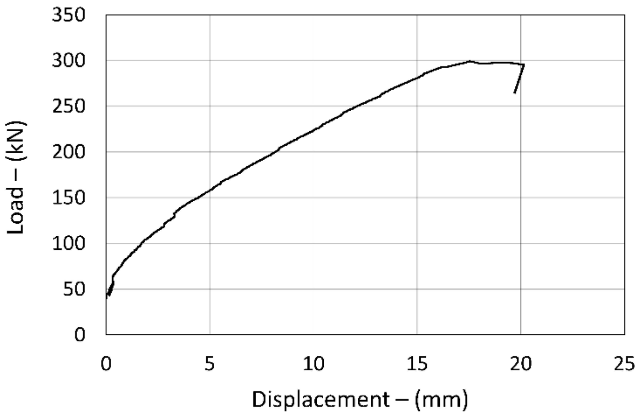

Figure 3. Specimen SO1-01. Load-deflection curve, LVDT number D1.

3.2 SO1-02

The second specimen was tested under combined vertical loading horizontal cyclic drifts. The vertical loading was kept constant to about the 50% of the punching strength. The specimen failed at the first cycle of 1% drift. The maximum horizontal load resulted equal to 37.2 kN (Figure 4).

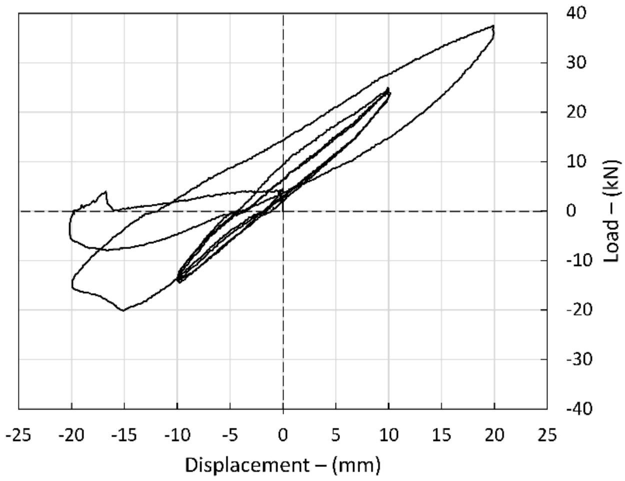

Figure 4. Specimen SO1-02. Load-displacement curve, LVDT actuator.

3.3 SO1-03

The third specimen was tested under the same conditions of specimen SO1-02, but SO1-03 was equipped with closed shear reinforcement (Figure 5).

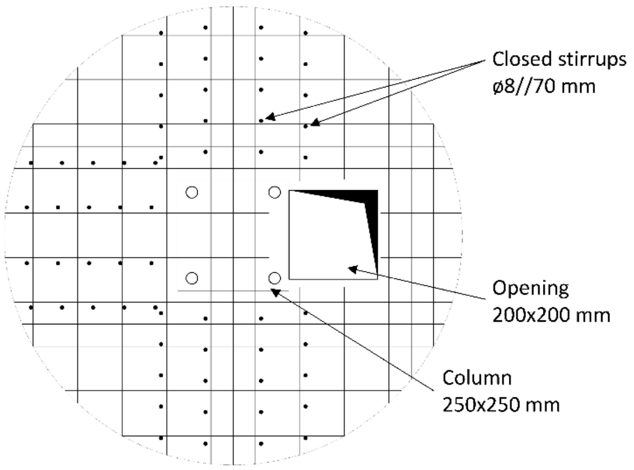

Figure 5. Shear reinforcement, specimen SO1-03.

The addiction of closed stirrups provided a small increase of the punching strength but it provided a substantial improvement of the slab-column ductility (Figure 6).

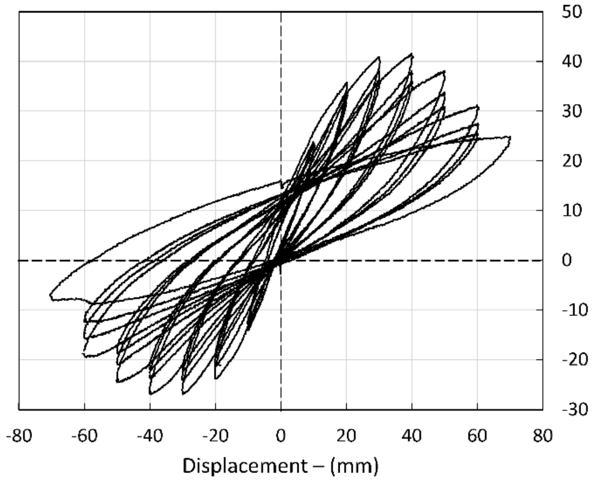

Figure 6. Specimen SO1-03. Load-displacement curve, LVDT actuator.

Actually the test was stopped at 3.5% of drift after a reduction of the horizontal load greater than 35%, however the punching failure was not achieved. Compared to the specimen SO1-02 the peak load resulted about 10 % higher while the drift 350% higher. The presence of the opening in north direction provided a very asymmetric response of the slab-column connection. For negative drift the peak load was about 25 kN while for positive drift resulted 42 kN.

4 EFFECTS OF OPENINGS

4.1 *Vertical loading*

Specimen SO1-01 presents almost the same characteristics of specimen MLS investigated by Almeida et al. (Almeida et al. 2016) except for the presence of the opening. The ultimate vertical loading of MLS resulted 323 kN, about 8% higher than the ultimate load of SO1-01.

However, considering the specific punching strength $v_r = V/b_0 \cdot d \cdot \sqrt{f_c}$, where b_0 is the control perimeter, d is the effective depth and f_c is the concrete compressive strength, the results provided by the two specimen are almost the same. In other words, assuming the same concrete compressive strength in both specimens, the reduction in punching strength due to the presence of the opening is correctly accounted by the reduction of the control perimeter (b_0).

4.2 *Seismic loading – No shear reinforcement*

Specimen SO1-02 presents almost the same characteristics of specimen C-50 investigated by Almeida et al. (Almeida et al. 2016) except for the presence of the opening. Despite for vertical loading the presence of the opening produces a reduction of the punching strength proportionally related to the reduction of the control perimeter, for seismic loading this relationship is not found.

Specimen C-50 reached the failure at 1% of drift for a peak load of 37.4 kN, almost the same results provided by SO1-02.

4.3 *Seismic loading – With shear reinforcement*

Specimen SO1-03 presents almost the same characteristics of specimen C50-STR4 investigated by Almeida et al. (Almeida et al. 2019) except for the presence of the opening. Specimen C50-STR4 reached a drift of 4% and exhibited a peak load of 58 kN. In this case the two specimens did not provide the same results, a substantial different is found in terms of horizontal peak load while the ductility resulted similar.

5 CONCLUSIONS

This work presents the preliminary results of a new experimental campaign dealing with the response of slab-column connections subjected to seismic loadings. The presence of the opening adjacent to the column is investigated. In the first series, including three specimens, the opening was placed in the horizontal load direction. The first specimen was tested under vertical loading while the other two were investigated under combined vertical and horizontal loading. The specimen SO1-03 included closed stirrups to investigate the beneficial effects provided by shear reinforcement.

For vertical loading the presence of the opening highly affects the punching strength. The reduction of the punching strength is proportional to the reduction of the control perimeter. For seismic loading this direct relationship is not found. The comparison of experimental results on slabs with and without openings, shows that the presence of the opening has little effect on the seismic behaviour of slab-column connections.

REFERENCES

ACI-ASCE Committee 421. 2010. ACI 421.2R-10 Guide to Seismic Design of Punching Shear Reinforcement in Flat Plates.

ACI Committee 318. 2014. Building Code Requirements for Structural Concrete (ACI 318M-14) and Commentary (ACI 318RM-14). Farmington Hills, U.S.A.

Almeida, A., Inacio, M., Lucio, V. and Ramos, A., 2016. Punching Behaviour of RC Flat Slabs under Reversed Horizontal Cyclic Loading. *Engineering Structures*, **117**, 204–219.

Almeida, A., Marreiros, R., Ramos, A., Ornelas, M. and Alcobia, B., 2019. Behaviour of RC Flat Slabs with Stirrups under Reversed Horizontal Cyclic Loading. *Magazine of Concrete Research* (in press).

Broms, C., 2009. Design Method for Imposed Rotations of Interior Slab-Column Connections. *ACI Structural Journal*, **106**(5), 636–645.

CEB/FIP. 1993. Ceb-Fip Model Code 1990. London, Thomas Telford.

Drakatos, I., Muttoni, A. and Beyer, K., 2018. Mechanical Model for Drift-Induced Punching of Slab column Connections without Transverse Reinforcement. *ACI Structural Journal*, **115**(2), 463–474.

El-Salakawy, E., Polak, M. and Soliman, M., 1999. Reinforced Concrete Slab-Column Edge Connections with Openings. *ACI Structural Journal*, **96**(1), 79–87.

Hanson, N. and Hanson, J., 1968. Shear and Moment Transfer Between Concrete Slabs and Columns. *Journal of the Portland Cement Association*, **10**(1), 2–16.

Hawkins, N., Mitchell, D. and Hanna, S., 1975. The Effects of Shear Reinforcement on Reversed Cyclic Loading Behavior of Flat Plate Structures. *Canadian Journal of Civil Engineering*, **2**(4), 572–582.

Lapi, M., Fernandes, H., Orlando, M., Ramos, A. and Lucio, V., 2017. Performance Assessment of Flat Slabs Strengthened with a Bonded Reinforced Concrete Overlay. *Magazine of Concrete Research*, **70**(9), 433-451.

Lapi, M., Orlando, M., Spinelli, P. and Ramos, A., 2019. Static and seismic behaviour of R/C slabs with openings adjacent to columns. *Proceedings of the fib Symposium 2019 Concrete - Innovations in Materials, Design and Structures*, 1795–1802.

Mast, P., 1970. Stresses in Flat Plates Near Columns. *ACI Journal*, **67**(10), 761–768.

Megally, S. and Ghali, A., 2000. Punching Shear Design of Earthquake-Resistant Slab-Column Connections. *ACI Structural Journal*, **97**(97), 720–730.

Moe, J., 1961. Shearing Strength of Reinforced Concrete Slabs and Footings under Concentrated Loads. *Journal of Portland Cement Association, Research and Development Laboratories*, D47, 130p.

Pan, A. and Moehle, J., 1989. Lateral Displacement Ductility of Reinforced Concrete Flat Plates. *ACI Structural Journal*, **86**(3), 250–258.

Stamenkovic, A. and Chapman, J., 1974. Local strength at column heads in flat slabs subjected to a combined vertical and horizontal loading. *Proceedings of the Institution of Civil Engineers*, **57**(2), 205–232.

Di Stasio, J. and Van Buren, M., 1960. Transfer of Bending Moment between Flat Plate Floor and Column. *ACI Journal*, **32**(3), 299–314.