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SUDDEN CHANGE OF THE CROSS-SECTION OF REINFORCED CONCRETE COLUMN AT SLAB LEVEL: EXPERIMENTAL INVESTIGATION

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ABSTRACT
Architects prefer the square or circular cross-section of the reinforced concrete (RC) columns in the garages or commercial floors in building. However in the upper residential floors, they prefer the elongated rectangular sections to be embedded in the partition walls. Therefore, the cross section of the RC columns may change suddenly between the floors. This study introduce a first attempt to investigate the behavior under compression of RC columns with sudden change of the cross section at the slap level. Five RC column specimens were tested under concentric loading. The columns have square cross-sections at the lower part and change to rectangular cross section with the same area at the upper part. Some specimens have short cantilevers at the top head of the lower columns Variable parameters were studied as the slab confining effect, the reinforcement, and the short cantilever depth. Loads, axial displacement, strains, and failure patterns were studied for each column specimen. The results indicate that this system can be used in construction with some provisions about the steel ties distribution and the overlap length. The presence of the slab and steel ties are very effective to increase the axial capacity of the connection. Also, increasing the short cantilever depth is able to increase the ultimate capacity up to a certain depth equals the offset of the upper column edge from the lower column edge.

KEYWORDS: Column, Concentric load, Confinement, Construction.

INTRODUCTION
Administrative and commercial buildings have commonly different architectural partitions and design for each floor depending on the use of each floor. For each floor, the structural system and the distribution of columns may change to achieve the architectural use of each floor. Therefore, the structural engineers have to be flexible to provide accurate and safe design without disturbing the architectural design. One of the common problems is that the reinforced concrete (RC) columns have to have square or circular cross-section in garage or commercial floor for maneuvering and spacing purposes. However in the upper residential floors, the columns need to be elongated be embedded in the partition walls. Therefore, the cross section of the RC columns may change suddenly between the floors at the slab levels. For example, if a column section at the first floor is 500×500 mm^2, the cross section of this column at the upper second floor will be 250×1000 mm^2. That means, there is an offset equals 250 mm between the upper column edges to the lower column edges, in addition, the direct bearing area between the two column's parts is condensed to 250×500 mm^2. In this case, designers must be careful to transfer vertical load safely from the upper column to the lower column.

Designers used to provide strong RC beams to transfer smoothly the loads from the upper column to the lower column. These strong beams may disturb the architectural requirements as the air-conditioning ducts, electrical pipes, and permissible clear heights. Clever designers may use the strut-and-tie design method [1 to 4] or finite element analysis to design this type of connection [5].
In fact, no research was found that investigates experimentally that type of connection between two different cross-sections of the same column. The authors in this study introduce a first attempt to investigate experimentally the behavior under compression of RC columns with sudden change of the cross section at the slap level [6 and 7]. In this paper, five RC column specimens were tested under concentric loading. The columns have square cross-sections at the lower part and change to rectangular cross section with the same area at the upper part. Variable parameters were studied as the slab confining effect, the reinforcement distribution, and the overlap length between the column's parts, which simulates a short cantilever at the top head of the lower column. Loads, axial displacement, strains, and failure patterns were studied for each column specimen. More details are illustrated in the following sections.

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EXPERIMENTAL PROGRAM

Column Specimens

Five column specimens (C0a, C1a, C2a, C3a, and C4a) were prepared for this paper as shown in Figures 1 to 5 and Table 1.

All the columns contain:

1) Upper column with 100×400 mm^2 cross section and 600 mm height and reinforced with 8Ø10 as vertical steel reinforcement and 1Ø6/100 mm as stirrups along its height.
2) Lower column with 200×200 mm^2 cross section and 400 mm height and reinforced with 4Ø12 as vertical steel reinforcement and 1Ø6/100 mm as stirrups along its height (Note, the two columns have the same cross-section area).
3) Additional stirrups 1Ø8/25mm were put at the top and bottom ends of the upper column and lower column, respectively, to strengthen those regions and to prevent the local splitting action at the specimen ends during the test.
4) Slab (in C1a, C2a, C3a, and C4a only) with 550×550 mm^2 area and 50 mm thickness and reinforced with 1Ø4/50mm as top and bottom mesh.

Additional stirrups 1Ø6/25mm were provided in C2a at the top of the lower column only (below the slab bottom) for a distance equals 150 mm to study the effect of increasing the reinforcement at the connection zone. An overlap (L_o) between the upper and lower columns simulated as a short cantilever at the top head of the lower column was provided in specimens C3a and C4a only. In C3a, the overlap (cantilever depth) equals the offset (L_c) between the upper column edge and the lower column edge (L_o=L_c=100mm). While in C4a, L_o=1.5L_c=150mm. Moreover, additional stirrups 1Ø6/25mm were provided in C3a and C4a below the slab bottom for a distance equals 150 mm. Table 1 shows the test matrix and the particular studied parameter for each column specimen.

Table 1: Test matrix

Column	Configuration	Studied parameter
C0a	Without slab, without additional stirrups	The slab confining effect
C1a	With slab, without additional stirrups	
C2a	With slab, With additional stirrups	Reinforcement distribution
C3a	With slab, With additional stirrups	Cantilever depth L_o=L_c=100mm
C4a	With slab, With additional stirrups	Cantilever depth L_o=1.5L_c=150mm

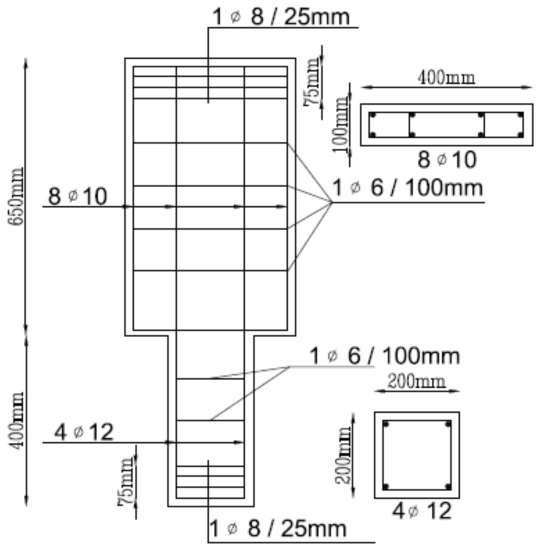

Figure 1: Details of specimen C0a

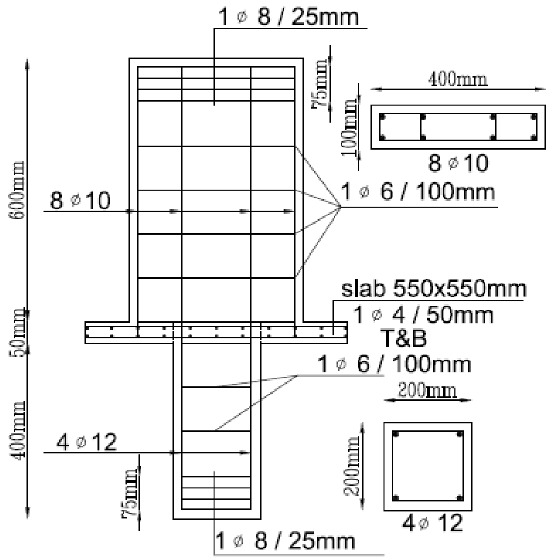

Figure 2: Details of specimen C1a

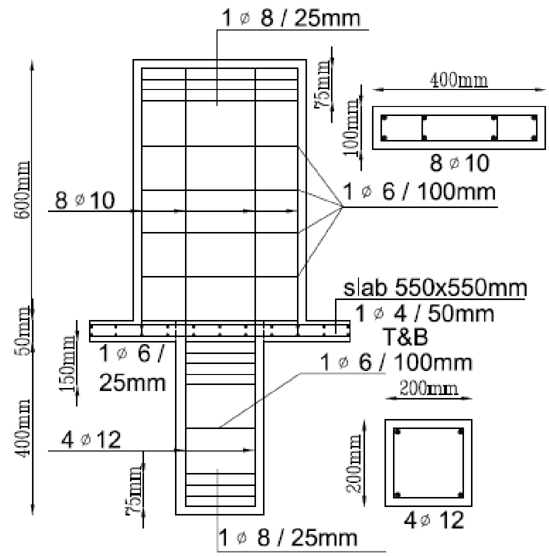

Figure 3: Details of specimen C2a

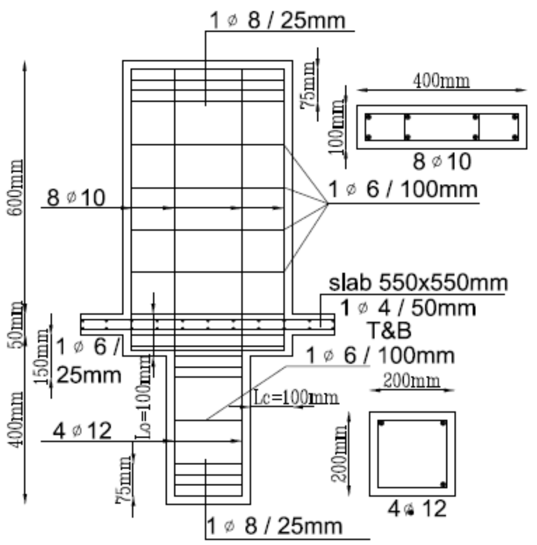

Figure 4: Details of specimen C3a

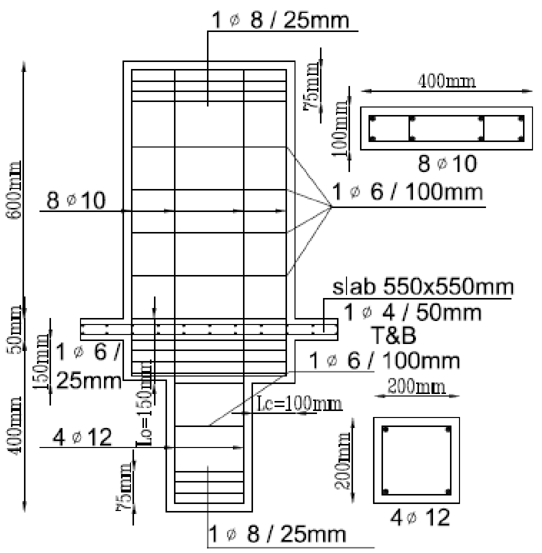

Figure 5: Details of specimen C4a

Used Materials

Natural crushed stone is used as gravel, which has a maximum nominal size of 10 mm. Natural sand is also used. The mix proportion by weight between gravel: sand: cement: silica fume: water is 11: 6: 4.6: 0.4: 1.4. The characteristic compressive strength of concrete standard cubes is 45 MPa. Steel used to reinforce the columns has the properties listed in Table 2.

Table 2: Properties of used steel

Ø (mm)	Yield stress (MPa)	Ultimate stress (MPa)	Elongation (%)
4	----	747	7.3
6	286	459	24.3
8	273	380	26
10	410	615	12.5
12	390	560	13

Instrumentations and Test Setup

The columns were tested under concentric loading using a hydraulic jack of 3000 kN capacity. Four linear variable differential transducers (LVDTs) were fixed to measure the vertical displacement. Eight Demec points were glued in two rows at the surface of upper columns to record the vertical and horizontal strains and cracks width, as shown in Figure 6. In addition to Demec points, four electric strain gauges were glued on the concrete surface of upper column; three of them to measure vertical strains, and the fourth one to measure horizontal strain. Before casting, electric strain gauge was bonded over a stirrup at 200 mm over the slab top surface in C2a, C3a, and C4a. All instrumentations were connected with acquisition system to record and save the readings automatically. The columns ends were confined by steel angles to strengthen those regions during the test and prevent any local failure at them. A steel spreader I-beam was used to distribute the applied load uniformly on the cross section of the upper column. The columns heads were flattened by gypsum cap for uniform distribution of the stresses. The columns were positioned vertically as shown in Figure 6. Load increments were recorded in the computer program and consequently were applied on the columns with a loading rate of 10 kN/min.

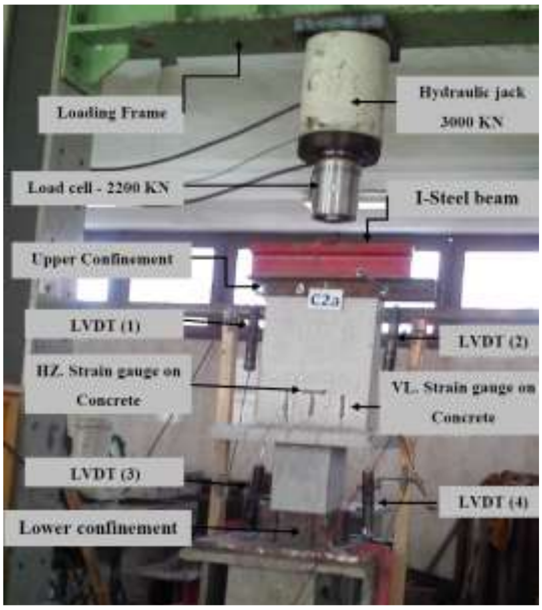

Figure 6: Test setup

TEST RESULTS AND DISCUSSION

Failure Pattern

C0a, without slab, failed by excessive bearing stress at the top of the lower column part. C1a, with slab but do not have concentrated stirrups, failed in more ductile way than C0a by crushing at the top of the lower column and cracks at the upper column. Generally, all columns with slab indicate more ductile failure and failed typically like the strut and tie model indicated in Figure 7. First, vertical tension cracks occurred at the tension zone of the upper column. Then, compression failure by crushing of concrete in the struts zones.

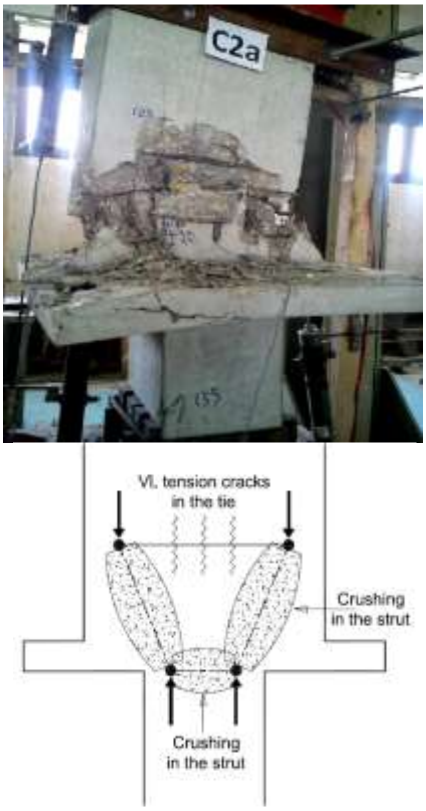

Figure 7: Typical failure pattern of C2a, C3a, and C4a

Load-Displacement Relationship

The load-axial displacement relationship for the studied columns have two different slopes as shown in Figure 8. The first slope began linear with a large vertical displacement, because of the large deformation of gypsum cap. The second slope continued linearly with small vertical displacement until failure. This means that all columns failed in compression, which agrees the true failure. As seen, the ultimate capacity increases with the presences of the slab. In addition, increasing the cantilever depth increases the capacity until a depth (L_o) equals the offset length (L_c) as shown in Figure 9.

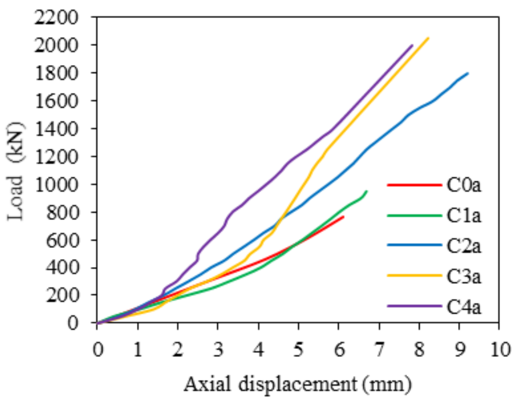

Figure 8: Load-displacement relationship

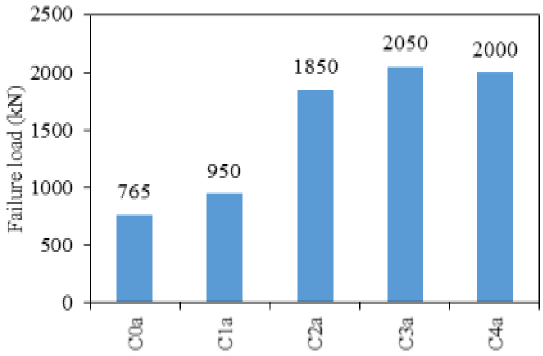

Figure 9: Failure loads

Vertical Strains in Upper Columns

Figures 10 to 12 show the load-vertical strains relationships for the columns C2a, C3a, and C4a. The figures show that the vertical strains are not equal at the same height level because of its position in the discontinuity region (D.R). When the overlap length (cantilever depth L_o) increased, the strain moved to the end of D.R and consequently the vertical strain go to be uniform, as indicated in column C3a and C4a. For column C2a, the vertical strain at the middle point is greater than the edge points because of the bearing effect where its position is over the lower column directly, while the other points lie in the flexible part. As seen, the length of the D.R can be measured from the lower point of overlap.

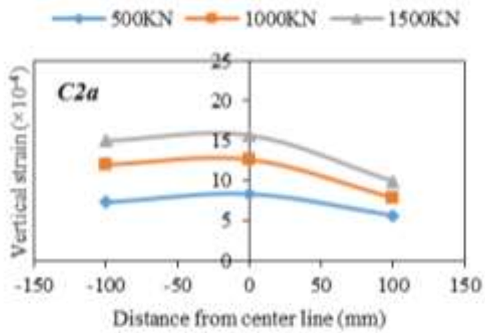

Figure 10: Vertical strains in C2a

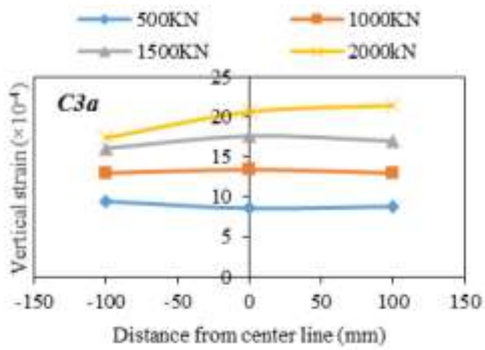

Figure 11: Vertical strains in C3a

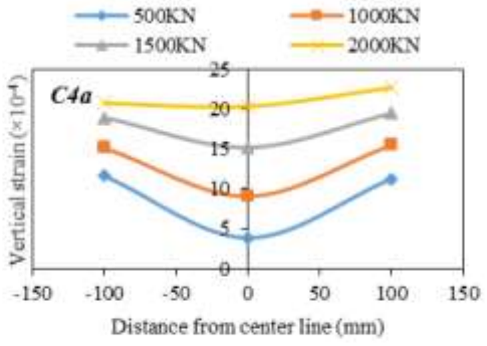

Figure 12: Vertical strains in C4a

Strains in the Stirrups of the Upper Columns

Figure 13 shows the load-strain relationship for the studied columns C2a, C3a, and C4a. The results indicate that stirrup that lies at 100 mm above the slab level in C2a yielded before that in C3a and C4a. This confirms the excessive tension vertical cracks that happened in C2a compared to C3a and C4a. At the same load level, the strain in C2a is more than that in C3a, C4a. This is attributed to the stirrup position in C3a and C4a that contain short cantilevers become far away from the D.R than in C2a that does not have short cantilever. In other meaning, the stirrup position in C2a was near to the tie position (in strut and tie model), then it had a larger strains. This also indicates that the D.R center is about 100 mm above the slab surface.

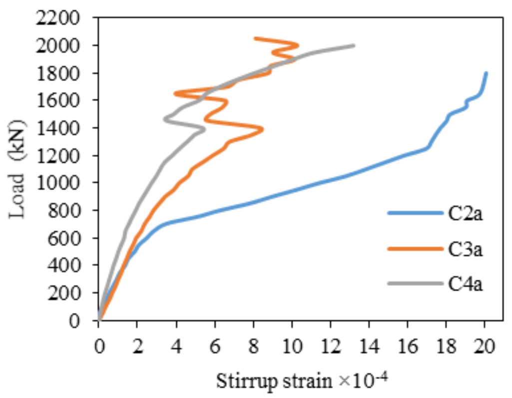

Figure 13: Horizontal strains in C2a, C3a, and C4a

Effect of Slab Presence

The ultimate load capacity of the columns and their mode of failure were used to study the effect of slab presence on the connection behavior by comparing C0a and C1a. Figure 14 shows the load-displacement of the two columns; C0a has a slab at connection and C1a without a slab. The ultimate capacity of C1a (with a slab) increases by about 24% than that of C0a (without a slab). Moreover, C0a failed early by bearing at the top head of the lower column. While C1a failed in more ductile way than C0a by crushing at the top of the lower column and vertical tension cracks at the upper column. This is attributed to:

1) The slab transferred the load smoothly from the upper column to the lower column.
2) The slab confined the top head of the lower column. This confirms the bearing failure of C0a without the slab unlike the more ductile failure of C1a.
3) The reinforcement mesh of the slab act as tie reinforcement in strut and tie model.

It is clear that the slab presence enhanced the connection behavior and led to increasing of load capacity.

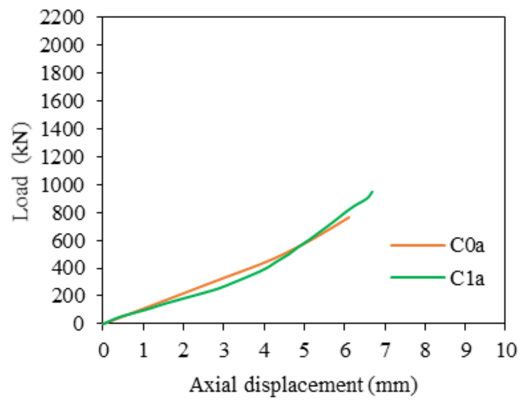

Figure 14: Effect of slab presence

Effect of Stirrups Concentration

Figure 15 shows the effect of stirrups concentration on increasing the load capacity by comparing C1a and C2a. The ultimate capacity of C2a (with stirrups concentration at the lower column head) increased by 95% higher than that of C1a without stirrups concentration. The reason is the more confining action on the lower column head. Moreover, the concentrated stirrups act as reinforcement in the compression strut at this zone, accordingly, the tie action act effectively where the horizontal stirrups yielded as shown in Figure 13. This means full utilization of the strut and tie model elements.

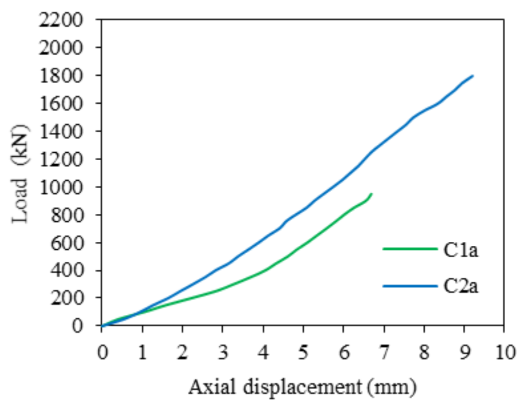

Figure 15: Effect of stirrups concentration

Effect of Cantilever Depth
Figure 16 shows the effect of the overlap length or the cantilever depth (L_o) on increasing the load capacity of the columns C3a and C4a compared to C2a. It was found that, the failure load of C3a (L_o=L_c=100mm) increased by 11% more than that of C2a which has overlap but embedded in the slab thickness. But When the overlap length became L_o=1.5L_c=150mm as in C4a, the load capacity increased by 8% more than that of C2a. The behavior of C4a can be interpreted by the far position of the slab away for the columns interface. Accordingly, the reinforcement action of the slab meshes was slightly eliminated when increasing the cantilever depth over the offset length L_c.

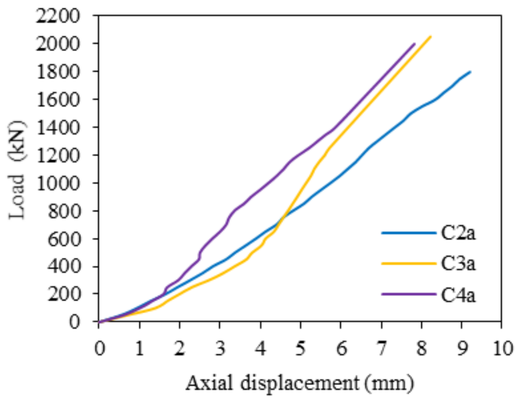

Figure 16: Effect of cantilever depth

CONCLUSIONS
This research is a first attempt that highlight the connection behavior in a column with sudden change of cross-section at the slab level. The main conclusions of this study can be summarized as follow:

1) The slab presence increases the failure load and improves the mode of failure.
2) Stirrups concentration is very effective in this type of connection.
3) The stirrups in the upper column must be increased at a distance equals at least the column long dimension to resist the horizontal tie action at this zone and increasing confinement for the concrete in upper column.
4) The stirrups in the lower column should be increased at a distance from its top equals at least the column long dimension to confine the concrete in the column and enhance the strut performance at this zone.
5) The height of the tie position is almost equal to the mid-length of the discontinuity region.
6) Increasing the overlap length or the cantilever depth is able to increase the load capacity.
7) It is preferable to choose the overlap length not more than the offset length to get benefit from the confining and reinforcement action of the slab. When the slab is far away from the columns interface, the connection behaves as in column C0a.

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