Research Article

Numerical Investigation of the Effect of Column Staggering in Flat Slabs Systems

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Abstract: In frame structures having beam supported cast in-situ concrete slabs, there is no flexibility in repositioning columns without compromising structural framing plan, to conserve space. Although, column repositioning is achievable in flat slabs, it is difficult to practice because of non-availability of design guidelines taking care of haphazardly placed columns or staggered column arrangement. Providing staggered columns under flat slab may reduce the labor as well as the material cost of the structure without affecting the structural performance of the slabs as well as columns. Wide parking and halls could be constructed and architects will have more freedom and flexibility in their designs with reduced reliance on structural design. This study is focused on the basic flat slab analyses and design with the help of finite element software along with manual method of analyses and design called "yield line method" applied to staggered column arrangement. To analyze more patterns in less time, finite element results has been validated with yield line method. Based on the analyses and design results for different case studies, column staggering guidelines have been developed and presented. To prove the concept, a numerical case study of a building with staggered columns arrangement has also been presented. As expected, it has been discovered that providing a column or eliminating a column at one location may disturb the deflection and moment of flat slab at other location, while it's possible to reduce the number of columns by staggering. The provided guidelines can be used to reduce risks of punching shear, bending moment and deflection at extreme corners and edges, while avoiding edge beams in flat slabs for staggered column arrangement.

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Introduction

Flat slabs are less labor intensive, simplify the installation of services, and can accommodate more floors within restricted heights. However, the span influencing their design is the longest (Turner, 1905; Nilson et al., 2003; Park and Gamble, 2000; Bhavikatti, 2008), and they require more steel compared to two-way slabs Patil and Rupali (2004). Other drawbacks Civiltoday (2014) of flat slabs are vulnerability to punching shear failure Suzanne et al. (2004) and higher deflections. To avoid punching shear failure, drop panels, column heads or shear reinforcement Shahram et al. (2018) are used. If span in flat slabs is reduced, then both deflection and punching shear problems can be avoided. However, architects prefer to have few exposed columns in usable areas. This inevitably leads to columns in an irregular layout, hidden inside partitions or walls Jianzeg et al. (2000). Considering the urban demands, the flat slabs built with columns in an irregular layout may help in constructing buildings that satisfy their functional requirements (Teng et al., 2000; Kathir, 2003).

The purpose of this research is to develop a practical method/guideline for analysis and design of staggered columns arrangement in flat slab. Methods involving trial and error, like yield line design (Ingerslev, 1923; Hillerborg, 1956; Corley et al.,1961; Johnson, 1999; Kirn and Lee, 2005; More and Sawant, 2015) (considering the slab with an assumed steel distribution and assessing the load capacity for possible yield line patterns), elastic finite element analyses (Guan and Loo, 1997) software (which results in peaky moments above columns and needs experience to perform redistribution) and nonlinear finite element software such as ETABS (2020) and SAFE (2020) have been assessed and used for design optimization (Hu et al., 2018; Qiong et al., 2017; Mohsen et al., 2017; Baskaran, 2007a) of staggered column flat slabs.

Design methods for flat slabs (BS8110, 1997; ACI Committee 318, 2011) supported on non-rectangular column layouts were attempted only in the early seventies (Van, 1971). Wood and Armer (1968), Kemp (1971) and Wiesinger (1973) proposed to divide the panel into triangular grid and calculate column and middle strip moments considering the equilibrium of loads transferred by each strip. An effective width method was proposed for flat plates by Choi and Song (2005) and a numerical approach by Park (1999) and Jayaprakash and Sreenivas (2015). One limitation of Wiesinger's approach is the assumption that lines connecting panel centers with columns as zero shear lines but the method has not got any moment calculations along those lines; instead it calculates the moments considering them as concentrated moments and distributed them according to direct design method ACI Committee 318, 2012. Further, one can argue if we always need to limit the division of slab panels to triangles (Moss, 2001), pentagons etc.? Reviews of flat slab strengthening for a variety of conditions including openings, damage, prestressing, anchorage length and punching zone are available (Robert et al., 2013) but variation of architectural shape has not been discovered yet, hence worked out in this research.

The guidelines produced in this research are independent of shape of slab and layout of columns. As the slab must be checked for flexural, shear and serviceability, the guidelines, thus developed cover all design requirements.

Column staggering involves repositioning, removal, splitting columns or their combination.

Numerical modeling of flat slab

Software validation: To validate the analysis and design results of Finite Element (FE) models developed in CSI ETABS and CSI SAFE, the flat slab shown in Figure 1 has been analyzed using these software as well as manually by Yield Line method. This flat slab has three bays in x-direction and four bays in y-direction. Each bay width in x-direction and y-direction is kept uniform which is equal to 7.5 m (24.6 ft). The story height is 3 m (9.8 ft) and thickness of flat slab is checked with ACI 318-11, Table 5 (c); which is 210 mm (8.26 in) but after many trials it is found that 250 mm (9.84 in) thickness of slab is more suitable. The interior column cross sectional area is kept constant which is 400×400 mm^2 (16×16 in^2) and the exterior column cross sectional area is 400×250 mm^2 (16×9.8 in^2) and 250×400mm^2 (9.8×16 in^2), respectively.

Comparison

Comparison between manual analyses method and FE software are shown in Tables 1-3. Table 1 shows the moment comparison of internal and external bay. As the difference between numerical analysis and software base analysis is 0.14% to 0.39% which is acceptable to precede the research work. Axial forces were also compared in Table 2 to check whether the numerical analysis has not much difference than software base analysis; but still the difference increased from 0.28% to 1.16% and decreased from -4.9% to -8.23%. Also, the numerical analysis and software base analysis were compared based on punching shear which ranges from -5.31% to 14%. These differences are acceptable because software analysis includes all the factors like poison ratio, secondary moments, temperature etc. so that is why there was little difference between the results of numerical and software base analysis.

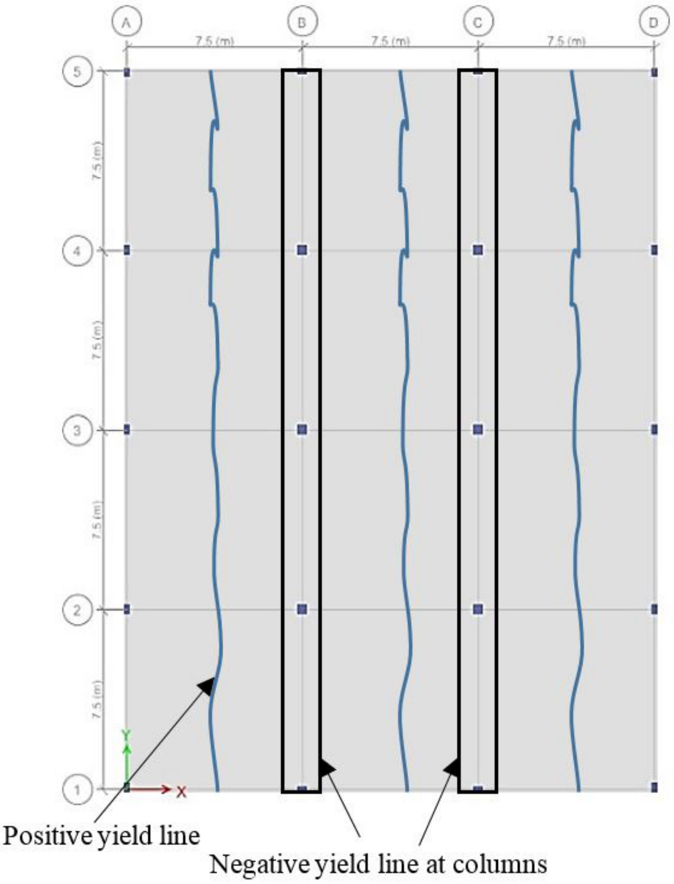


Figure 1: *Selected plan of flat slab for analysis and design validation.*

Table 1: *Moments comparison.*

Location	Yield line method kNm/m (kip-ft/ft)	ETABS V13 kNm/m (kip-ft/ft)	% Overestimation of ETABS V13
Internal bay	67.15 (49.52)	67.25 (49.6)	0.14%
External bay	42.95 (31.67)	43.12 (31.8)	0.39%

Table 2: *Axial forces comparison.*

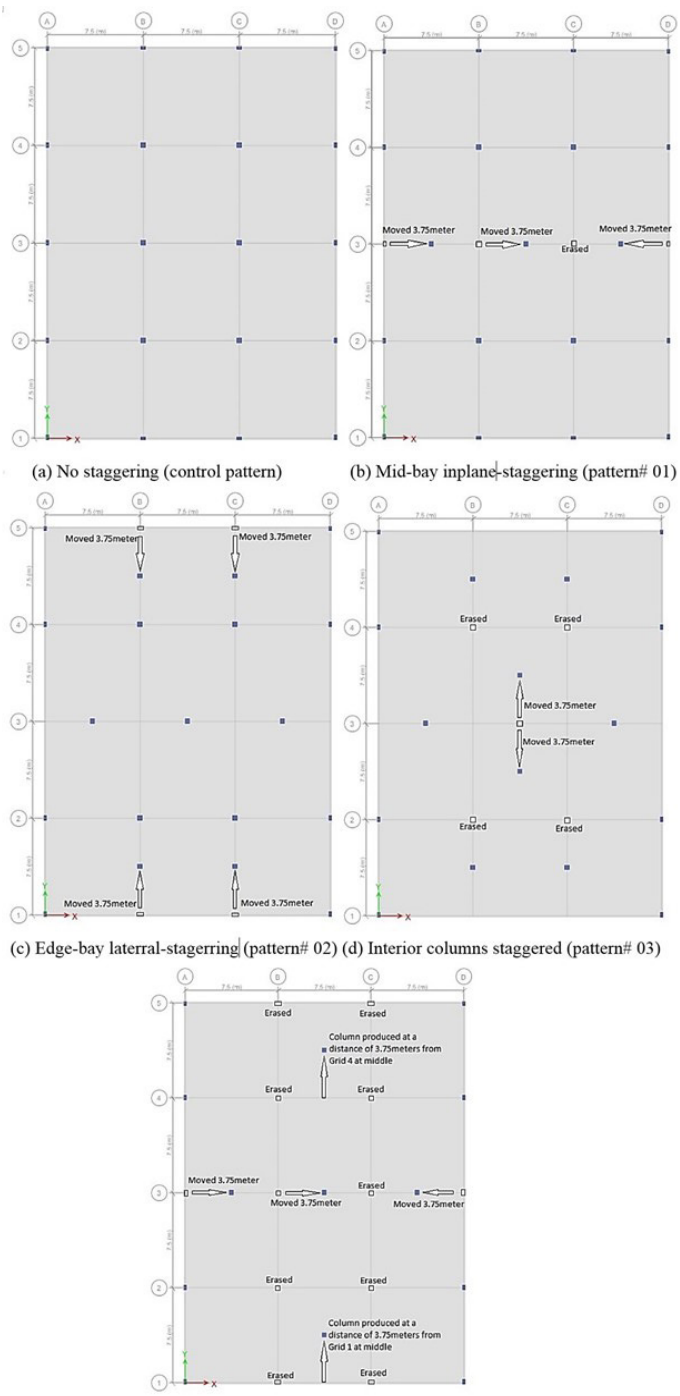
Column location	Yield line method kN (kips)	ETABS V13 kN (kips)	% Overestimation of ETABS V13
B2, C2, B4, C4	1000.51 (224.92)	1003.4 (225.57)	0.28%
B3, C3	868 (195.13)	877.89 (197.35)	1.12 %
A1, D1, A5, D5	180 (40.46)	182.12 (40.94)	1.16 %
A2, D2, A4, D4	405 (91.04)	385.05 (86.56)	-4.9 %
A3, D3	385.8 (86.73)	354.03 (79.59)	-8.23 %
B1, C1, B5, C5	405 (91.04)	384.25 (86.38)	-5.12 %

Column staggering analysis

Selection of patterns: Five different staggering patterns have been planned to study the effect of staggering in rectangular flat slabs as shown if (Figure 2a-e).

Table 3: *Punching shear comparison.*

Location of column	Yield line method D/C (Demand/Capacity) ratio	SAFE V12 D/C ratio	% Overestimation of SAFE V12
B2, C2, B4, C4	1.08	1.07	-0.92%
B3, C3	0.94	0.89	-5.31%
A1, D1, A5, D5	1.42	1.63	12.88%
A2, D2, A4, D4	0.71	0.81	12.34%
A3, D3	0.68	0.70	2.85 %
B1, C1, B5, C5	0.713	0.83	14 %



(a) No staggering (control pattern) (b) Mid-bay inplane-staggering (pattern# 01)

(c) Edge-bay lateral-stagerring (pattern# 02) (d) Interior columns staggered (pattern# 03)

(e) Edge, mid and interior staggering (pattern #04)

Figure 2: *Column configurations for rectangular flat slabs with five different staggering patterns.*

Table 4: *Serviceability, moment, punching shear comparison (with ETABS).*

Pattern #	Serviceability mm (in)		Moment (ratio)		Punching shear (ratio)	% cost comparison
			+ve	-ve		
	Allowable limit	Max deflection	D/C	D/C	D/C	
Control	20 (0.78)	6.9 (0.27)	0.37	0.85	1.04	0%
#1	20 (0.78)	7.3 (0.28)	0.57	0.31	1.03	-ve 0.10%
#2	20 (0.78)	11.2 (0.44)	0.37	0.80	0.94	+ve 0.50%
#3	20 (0.78)	7.5 (0.29)	0.36	0.80	0.92	-ve 0.71%
#4	20 (0.78)	18.4 (0.72)	0.63	1.54	1.93	-ve 1.94%

Note: D/C= Demand to capacity ratio.

First of all, a standard pattern has been selected called control pattern. Keeping in view the analyses results of control pattern, randomly different patterns have been selected and analyzed. According to ACI-318-08 maximum deflection is 20mm (0.78in) for 7.5m (24.6ft) span but 18mm (0.7in) has been taken for safety; pattern selections is based on the maximum deflection criteria.

The analyses have been carried out in ETABS V13 and then slab has been exported to SAFE V12 for calculating punching shear at different location on the slab.

Analysis results: Different patterns have been analyzed and their comparison of serviceability, bending moment, punching shear and cost are shown in Tables 4 and 5.

Table 5: *Cost Comparison.*

Sr. No.	Pattern	Price million (PKR)
1	Control pattern	2.44
2	Pattern# 01	2.43
3	Pattern# 02	2.45
4	Pattern# 03	2.42
5	Pattern# 04	2.39

In Table 4 the pattern (Control, 1, and 4) are very critical in punching shear. To reduce the punching shear some techniques would be adopted i.e. extra columns or drop panels should be provided. Furthermore, in Table 4 the pattern 3 is also critical in moment, so for controlling the moment in slab two techniques may be used i.e. provide beam or reduce the span length by providing extra column in the same row. Figure 3 shows the graphical comparison of the structural performance of all patterns acquired through ETABS.

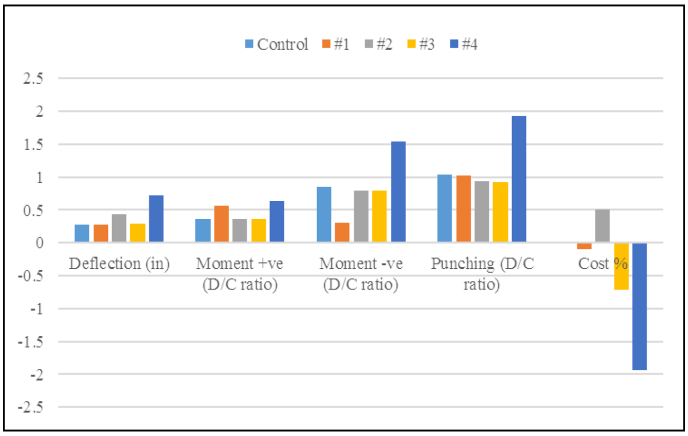


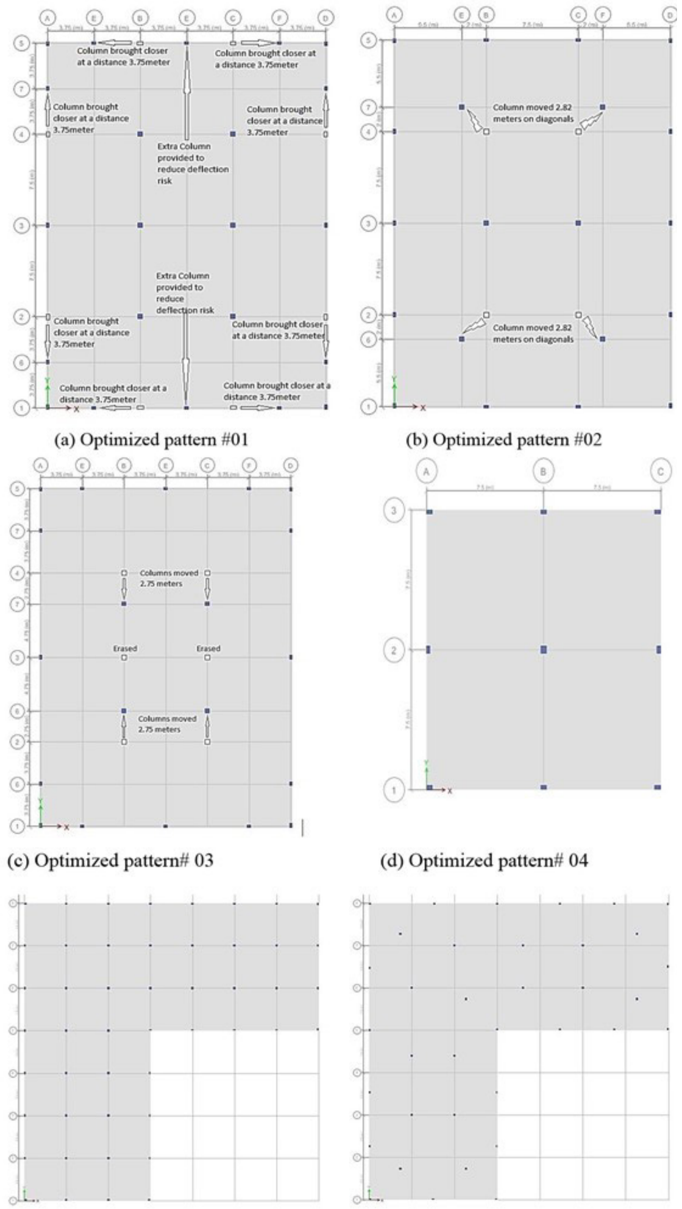
Figure 3: *Comparison of structural performance.*

Table 5 shows the cost comparison of different patterns when staggering techniques were applied. The cost difference is calculated based on the reduction or increase in number of columns due to staggering. Also, from Table 5 it may be clearly derived that staggering techniques provide a method to structure engineer to provide flexibility in dimension selection of a plan without any significant effect on cost. Furthermore, if possible extra shear rebar can control the punching shear as well.

Optimized patterns: Keeping in view the results of punching shear, some other pattern of staggered column has been studied to reduce the risks of punching shear easily. This study would help to make a valid arrangement of staggering columns for flat slab which could reduce the risk of punching shear without providing drop panels and column capitals. By rearranging column arrangement in control slab pattern, keeping the risk of punching shear, the following patterns were to be possibly placed.

- As the deflection on extreme edges was more critical so extra columns were provided as shown in Figure 4a.
- Interior columns are moved to reduce punching shear on extreme edges as shown in Figure 4b.

- Interior extra columns were removed to get maximum space as shown in Figure 4c.
- For such type of slab staggering has no effect as shown in Figure 4d.
- A complex control slab was selected for further analysis and checked according to previous techniques as shown in Figure 4e.
- Staggering techniques were applied on this slab. Columns were removed and added according to previous observations and the slab passed under service load as shown in Figure 4f.



(a) Optimized pattern #01 (b) Optimized pattern #02

(c) Optimized pattern# 03 (d) Optimized pattern# 04

(e) Optimized pattern# 05 (f) Optimized pattern# 06

Figure 4: *Optimized patterns of staggering.*

Column staggering guidelines

From the simulation, it has been observed that:

- At extreme edges of the slab i.e. vertex of the slab, punching shear is more critical compared to other locations.
- Comparing the cost by eliminating the columns may not reduce the cost, as major portion of the structure is slab. Compared to slab, the cost of columns is very low.
- There is no serious issue of deflection or moment in slab, but in such type of structures the punching shear is more critical.
- From the previous analyses of different patterns, it has been observed that changing the number of bays in x-direction or y-direction or changing slab pattern i.e. to right-angle (L-shape) may not affect the deflection or punching shear.
- With minimum number of columns, a slab can withstand safely under punching shear, the extreme corner of slab is mostly critical and deflection on extreme edges is also critical; so proper attention is required while removing columns in such areas.

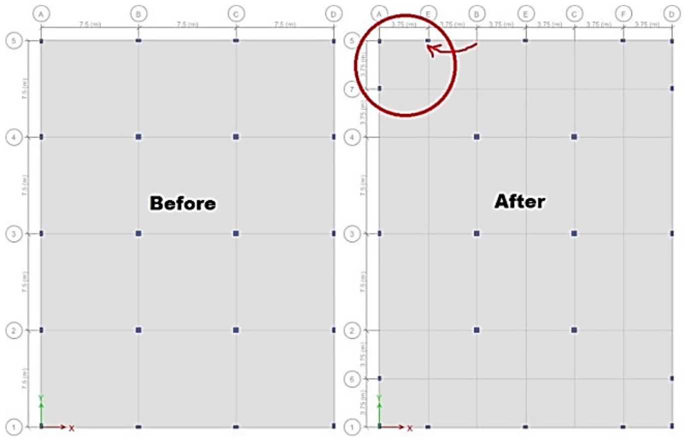


Figure 5: *Columns near corner edge brought closer.*

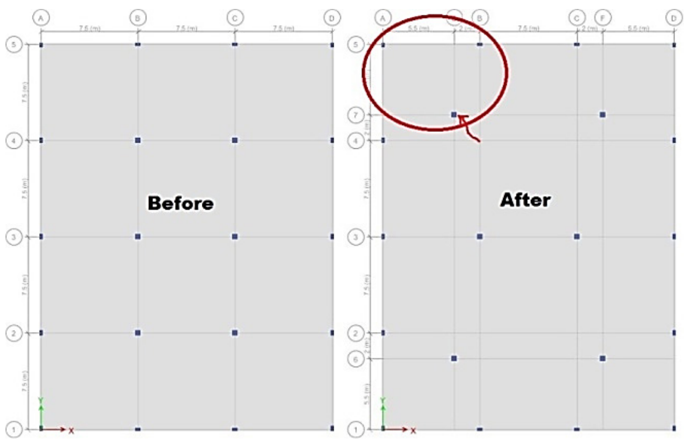


Figure 6: *Diagonally located column brought closer to the corner.*

Guidelines for column staggering

Punching shear on extreme corners could be controlled by the following two ways beside drop panels and column capitals:

- Edge columns near the corner may be moved close to the corner-column, as shown in Figure 5.
- A diagonally located column may be brought

closer to the corner-column at minimum 4 m (12 ft) diagonal distance, as shown in Figure 6.

- Depth of slab should be at least based on ACI 318 equation based on maximum span length.
- The behavior of slab in deflection changes by providing staggered columns which in turn affects the punching shear. So before staggering of columns the moment properties should be thoroughly studied.
- The distance between first two columns on extreme corners will not exceed ½ (span length) by which depth of slab is provided.
- Deflection on extreme edges is critical, so distance between columns should be kept according to ACI 318 provisions.
- Increase or decrease in number of bays may not affect the deflection or punching shear.
- The connection between slab as shown in Figure 7, would be consider as simple slab no special consideration required i.e. columns arrangement would be as staggered as discussed in this research. Increasing the number of bays in both directions would help to reduce the number of columns required to safely support the flat slab. Further study is possible to check and enhance the lateral stability of flat slab with staggered column arrangement i.e. earthquake load and wind load.

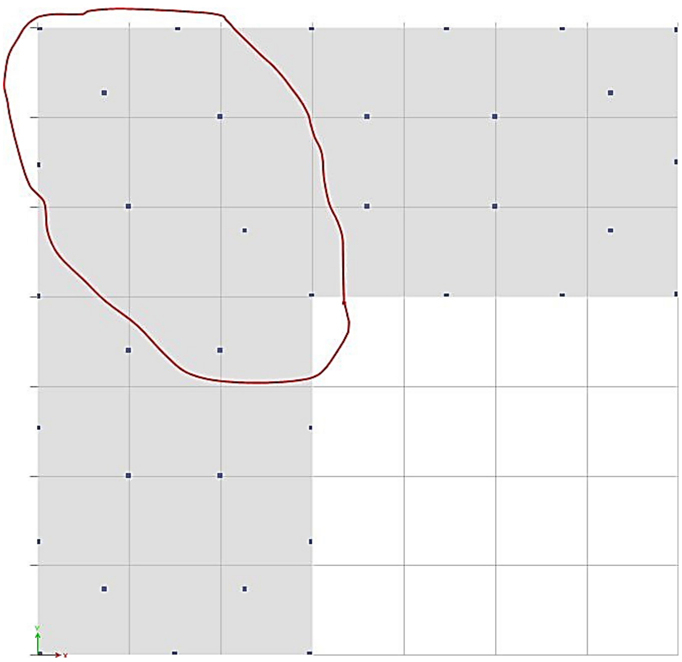


Figure 7: *Slab connection between two rectangular slabs.*

- Further study is possible to check this research for more than 3 story buildings or high raise buildings.
- A study is possible to reduce the risk of punching shear at extreme corners and serviceability at extreme edges by providing edge beam to flat slab with staggered column arrangement.
- A study is possible to provide staggered column arrangement in column beam, frame structure.

Conclusions and Recommendations

Following conclusions may be made based on the above studies:

- Computer aided analyses and design should be used to reduce time required for analyzing various patterns because there is a difference of 0.14% in moments of external bays and in internal bay there is a difference of 0.39% w.r.t computer aided software. Keeping in view the result of axial forces on columns head are also satisfactory i.e. the maximum increase is 8.23% and maximum decrease is 1.16% which is in both cases less than the mention criteria i.e. 10%. By comparing the punching shears with SAFE V12 the results are also satisfactory being on conservative side by 14%. Which shows that computer aided analyses are suitable for analyses of various patterns.
- It has been concluded that changing the number of bays in x-direction or y-direction or changing slab pattern i.e. to right-angle (L-shape) would not affect the deflection or punching shear. Punching shear on extreme corner of slab is mostly critical and deflection on extreme edges is critical; so proper attention is required while removing columns from such locations.
- Increasing number of stories, the deflection increases in similar bays.
- Compared to column beam arrangement, the number of columns also reduced which is very beneficial in cost optimization.
- Three story building can be safely designed by using these research techniques. Further addition of stories or increasing number of stories would need special considerations.
- This research could provide broad mind thinking to architects, because the restriction from structural design engineers were removed and columns could be placed anywhere in the proposed plan.
- Comparing the cost by eliminating the columns would not reduce the cost, as major portion of the structure was slab. Compared to slab the cost of columns was very low.
- From architectural point of view, more space was allowed for making hall and wide car parking.

- There were no serious issues of deflection or moment in slab but in such type of structures the punching shear would be more critical.
- Architects were not bound by the structure designers, as columns could be placed anywhere which will not affect the architectural look or room distribution.

Novelty Statement

Column staggering has unique cost and architectural benefits at the same time it becomes challenging to achieve in flat slabs. The best possibilities and cases of staggered columns in RC flat slabs has been investigated and presented in this paper.

Author's Contribution

Mohammad Adil: Research methodology and planning.
Muhammad A. Khan: Numerical modeling.
Naveed Ahmad: Modelling and drafting support.
Edward Bromhead: Original concept.
Muhammad A. Arshad: Review of flat slab analysis.
Muhammad Fahad: Review of flat slab analysis.
Shahid Ullah: Review of staggering pattern selection.
Khan Shahzada: Writeup.

Conflict of interest
The authors have declared no conflict of interest.

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