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**RESEARCH ARTICLE**

Engineering Reports

# Simplified Flat Slab Design with Irregular Columns Layout

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## Abstract

This paper presents a simplified design method (SDM) to analyze and design the flat plates with irregular column layouts. Theses flat plates having the irregular panels are subdivided into triangular panels. Flexural design formulas for largest triangular slab panel are derived based on the theoretical principles of plate and yield line theories and using the ultimate-strength design method USD under the provisions of ACI building code of design (ACI 318-14). Six different flat slabs with irregular column layouts (FS-1 to FS-6) are selected in this study to be analyzed and designed using the simplified design method approach. Numerical examples for two of the slabs (FS-3 and FS-6) are also presented to illustrate the method capability of designing the flat slabs having irregular column layouts. The selected slab sections (FS-1 to FS-6) are also analyzed and designed using the computer software (SAFE) and the results obtained are compared with the numerical solutions. The percentage difference of simplified design method with the finite element software (SAFE) ranges within 4% to 20% indicates that the SDM is a good and quick approach to design a flat slab having arbitrary/irregular column layout.

## KEYWORDS

Irregular columns layout, Flat slabs, Triangular Panels, Simplified design method.

## 1 | INTRODUCTION

Reinforced concrete slabs are the most important structural component in the construction industry and the most common practice to design any reinforced concrete slab is to start with the selection of slab type (one way slabs, two way slabs, waffle slabs, flat slabs or pre-cast or pre-stressed slabs) [1]. The most

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common type of slabs used in the construction industry is the flat slab due to the dominancy of slab–column connection in the general behaviour of flat slab. Flat slab is also an ease for the contractor to construct in shorter duration. The flat slab sections with regular column layout are the most common type of RC structures in the construction industry and it's also the choice for the contractor to construct the building with regular column layouts. There are scenarios where the building needs to be constructed having the irregular column layout based on the client's preference.

There are several studies on analysis and design of slabs with irregular column layouts. Baskaran, K. [2] in his research study introduced the structural membrane approach to design the flat slab on irregular column grid. Further, he also performed some experimental results to validate his theoretical approach. Hillerborg, Arne [3]in his book introduced the strip method of design for design of slabs having Irregular plan or that carry unevenly distributed loads. Saether [4] proposed an effective method for determining the bending moments in flat plates. He also developed an analytical design without the use of empirical formulas. His proposed method made it possible to analyse irregular plates with regular column layouts but gave an approximate results for irregular column layout flat slabs. Wang and Teng [5] in their research study presented a finite element analysis of reinforced flat plate using the flexible layering scheme. This proposed study is capable of analysing flat plate, flat slab with drop panels and large size flat plate with irregular columns layout. Aldwaik M. and Adeli H. [6] presented the cost optimization of reinforced concrete flat slabs for irregular high rise building structures. This proposed model automates the design process of RC slabs in addition to the cost optimization. The other similar research studies can be found elsewhere [7, 8, 9].

This study proposed a simplified method to analyse and design the flat plates with irregular column layout by first subdividing the irregular panels into triangular panels (figure-1) and then design the largest triangle slab panel using the ultimate-strength design method USD under the provisions of ACI building code of design (ACI 318-14) [10]. This simplified and quick approach will be useful for the designers to quickly analyse and design the flat slabs having the irregular column layout to fulfil the client's requirement. Moreover, this simplified method approach will also be useful for the educational purposes where the students can easily analyse and design the flat slabs having the irregular column layout.

The design of flat slabs with irregular column layout is based on structural safety and economy. Flexural design formulas are derived based on the theoretical principles of plate and yield line theories and ACI building code of design constraints [11, 12, 13]. Numerical examples are presented in this study to illustrate the method capability of designing the flat slabs having the irregular column layout. Six different flat slabs with irregular columns layout (FS-1 to FS-6) are selected to be analysed and designed using the simplified design method approach. The complete analysis and design for two of the flat slabs (FS-3 and FS-6) are also

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provided in this study. Mathcad software [14] is used in this research work to formulate this simplified design approach.

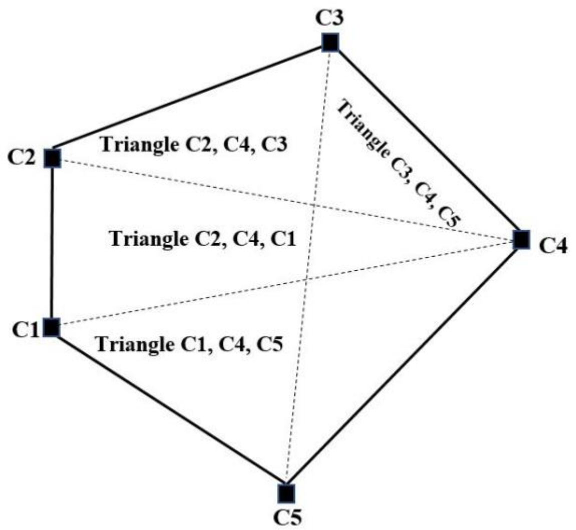


**Figure 1:** Flat slab with irregular column layout

The selected slab sections (FS-1 to FS-6) are also analysed and designed using the computer software (SAFE) and the results obtained are compared with the SDM numerical solutions.

## 2 | STUDIED FLAT SLAB MODELS

The selected six flat slab models having irregular columns layout is shown in figure-2 *(a to f)*. The concrete compressive strength $(\boldsymbol{f'_c})$ and the steel yield strength $(\boldsymbol{f_y})$ for these slabs are 30 MPa and 400 MPa respectively. The columns presented in the flat slab models are having the dimensions of (500 mm x 500 mm). Also, the elastic modulus of steel ***(E)*** and the density of concrete $(\gamma_c)$ used in this study are $200{,}000\ MPa$ and $25\ kN/m^3$.

## 3 | FLEXURAL DESIGN MOMENT EQUATIONS:

The following design steps need to be executed to determine the slab adequacy having irregular column layout.

**Step-1:** Divide the slab into suitable triangles and select the triangle with the biggest span length "***L***" and linear load "***W***".

**Step-2:** Minimum slab thickness $\boldsymbol{H_{min}}$ (ACI 318-14 code for minimum thickness)

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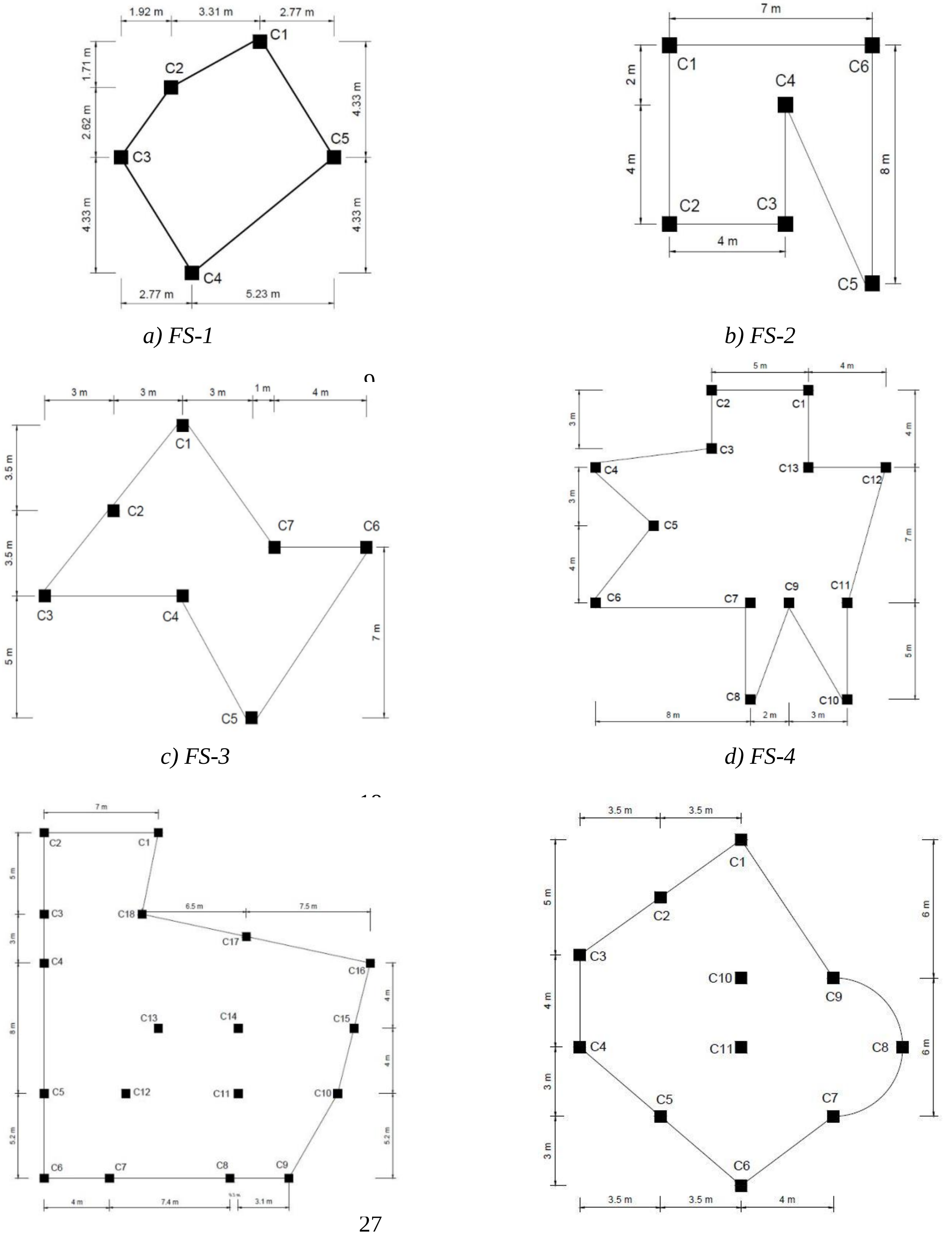


*a) FS-1* *b) FS-2*

*c) FS-3* *d) FS-4*

*e) FS-5* *f) FS-6*

**Figure 2 :** Flat Slab Models with Irregular Column Layout

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**Step-3:** Determine Ultimate Moment $\boldsymbol{M_U}$ (figure 1-a)

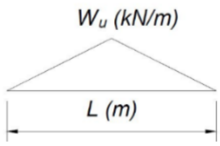


Figure 1-a: Ultimate Load on Triangular section

Ultimate Moment = $M_u = \frac{W_u L^2}{8}$

**Step-4:** Determine the required depth in flexure for Ultimate design Moment ($\boldsymbol{M_{Ud}}$).

$$d_{flex} = \sqrt{\frac{M_{Udes} \times 10^6}{k \times f_c' \times 1000}} \tag{1}$$

Where;

$$k = 0.765 \times 0.375 \times \beta \times \left(1 - \frac{0.375 \times \beta}{2}\right)$$

And,

$$\beta = 0.85 \;\; for \;\; \boldsymbol{f_c' \leq 30\, MPa}$$

$$\beta = 0.85 - 0.008(\boldsymbol{f_c'} - 30) \geq 0.65 \;\;\; for \;\; \boldsymbol{f_c' > 30\, MPa}$$

**Step-5:** Finding the required depth for one way shear, $\boldsymbol{V_{u(1)}}$.

$$V_c > V_{u(1)} \tag{2}$$

Where,

$$V_c = \emptyset_s \times {}^1/_6 \times \sqrt{f_c'} \times 1000 \times (H_{design} - d') \tag{3}$$

*(ACI 318-14 code for shear calculation)*

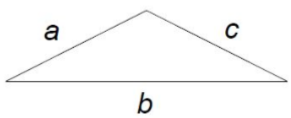
And,

$$V_{u(1)} = W_u \times L_p$$

$$L_p = \frac{L}{2} - \frac{Column\ width}{2}$$

**Step-6:** Finding the two way shear depth to satisfy punching shear requirement.

$$s = \frac{1}{2}(a + b + c)$$




$$A = \sqrt{s \times (s - a) \times (s - b) \times (s - c)}$$

$$V_{u(2)} = A \times W_u \tag{4}$$

$$r_{max} = \frac{V_{u(2)}}{\emptyset_s \times 1 \times (H_{design} - d') \times \left(\frac{2}{6} \times \sqrt{f_c'}\right)} \tag{5}$$

$$r_{max} < 1$$

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**Step- 7:** Calculate the required design depth which is the maximum required depth from steps 4 to 6.

**Step-8:** Check the approximate deflection in the slab and compare the deflection results with the ACI 318-14 code limits.

$$\delta_{approx} = \frac{M_s}{8 \times E_c \times I}\left[\left(\sqrt{L^2 + b^2}\right) - 2 \times Col_{width}\right]^2 \qquad (6)$$

$$\Delta_{code} = \frac{L}{360} \qquad (7)$$

**Step-9:** Steel area for the moments ***As***

$$As = \frac{Mu}{\varphi_b \ fy \left(d - \frac{a}{2}\right)} \qquad (8)$$

Where;

$\boldsymbol{\varphi_b}$= Bending reduction factor

$\boldsymbol{fy}$ = Specified yield strength of nonprestressed reinforcing

$\boldsymbol{As}$ = Area of tension steel

$\boldsymbol{d}$ = Effective depth

$\boldsymbol{a}$ =Depth of the compression block

Also,

$$d_S^L \le d \le d_S^U \qquad (8\text{-a})$$

$$As_S^{Mini} \le As \le As_S^{Max} \qquad (8\text{-b})$$

$$As^{Max} = 0.75 \times \beta 1 \times \frac{f`c}{fy}\left(\frac{600}{600 + fy}\right) bd \qquad (8 - c)$$

$$As^{Mini} = \left(\frac{1.4}{fy}\right) bd \qquad (8 - d)$$

Where $d_B^L$ and $d_B^U$ are slab depth, lower and upper bounds, and $As_B^{Mini}$ and $As_B^{Max}$ are slab steel reinforcement area, lower and upper bounds.

**Step-10:** Nominal slab strength Check $\emptyset\, \boldsymbol{M_N^-} = \boldsymbol{M_C^-} > \boldsymbol{M_U^-}$

$$M_c = \emptyset_b A_s f_y \left(d - \frac{a}{2}\right) \qquad (9)$$

Where;

$$a = \frac{A_s f_y}{0.85 f_c' b}$$

**Step-11:** Slab reinforcement detailing.

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## 4 | DESIGN RESULTS AND DISCUSSIONS

The design results for the studied six flat slabs having irregular column layout are illustrated in Table-1. These slabs are also analysed and designed using the computer software (SAFE) and the results obtained using the simplified design method are also compared with the SAFE software results. Moreover, the deflection results obtained in each slab is compared with the ACI code limit (L/360) and are shown in the last column of table-1. The deflection results showed that all of the six selected slab sections have deflection values less than the allowable deflection according to the ACI code of design (ACI 318-14) indicating good and safe design. The detailed design for two of the slabs (FS-3 and FS-6) are also provided in this section. The deflection contours for the studied slab models obtained from the SAFE software are shown in figure-3.

**Table 1:** Design results for flat slab models with irregular column layout

| Plate No. | Ultimate Load *(kN/m2)* | Thickness **H** *(mm)* | Design Items | Simplified Design Method | SAFE Software | Deflection Code Limit (mm) |
|---|---|---|---|---|---|---|
| **FS-1** | 10 | 300 | Mu (kN-m) | 108 | 101 | |
| | | | $r_{max}$ | 0.5 | 0.7 | |
| | | | Punching Shear | Pass | Pass | |
| | | | Deflection (mm) | 10.4 | 2.75 | 25 |
| **FS-2** | 10 | 270 | Mu (kN-m) | 67.27 | 40 | |
| | | | $r_{max}$ | 0.37 | 0.423 | |
| | | | Punching Shear | Pass | Pass | |
| | | | Deflection (mm) | 7.66 | 2.75 | 22.222 |
| **FS-3** | 10 | 290 | Mu (kN-m) | 71.169 | 59 | |
| | | | $r_{max}$ | 0.412 | 0.97 | |
| | | | Punching Shear | Pass | Pass | |
| | | | Deflection (mm) | 11.301 | 3.2 | 23.9 |
| **FS-4** | 10 | 270 | Mu (kN-m) | 80.6 | 70 | |
| | | | $r_{max}$ | 0.5 | 0.58 | |
| | | | Punching Shear | Pass | Pass | |
| | | | Deflection (mm) | 7.66 | 2.75 | 22.222 |
| **FS-5** | 10 | 300 | Mu (kN-m) | 101.3 | 132 | |
| | | | $r_{max}$ | 0.755 | 0.553 | |
| | | | Punching Shear | Pass | Pass | |
| | | | Deflection (mm) | 8.5 | 3.2 | 24.722 |
| **FS-6** | 10 | 270 | Mu (kN-m) | 72.8 | 96 | |
| | | | $r_{max}$ | 0.4 | 0.6 | |
| | | | Punching Shear | Pass | Pass | |
| | | | Deflection (mm) | 15.636 | 1.65 | 21.11 |

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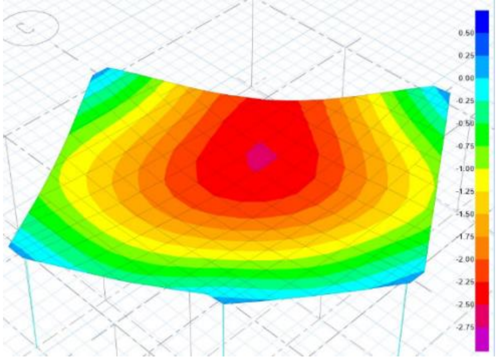
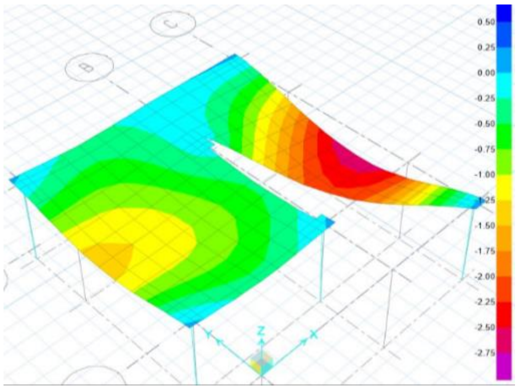
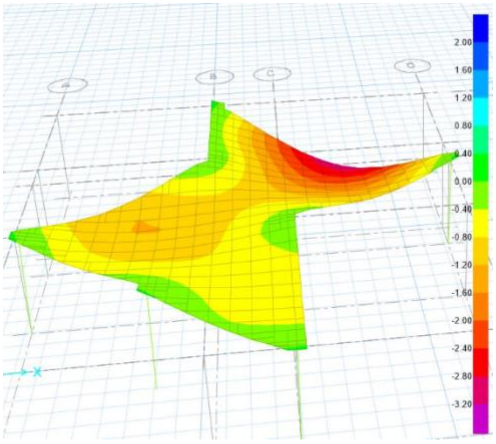


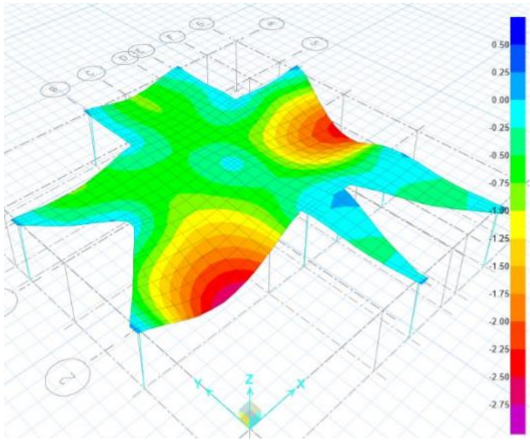
a) FS-1



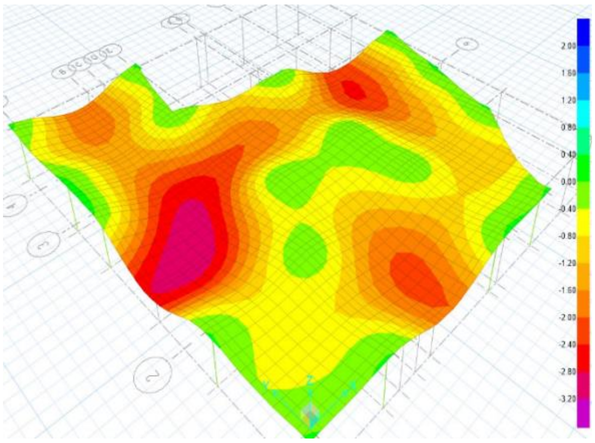
b) FS-2



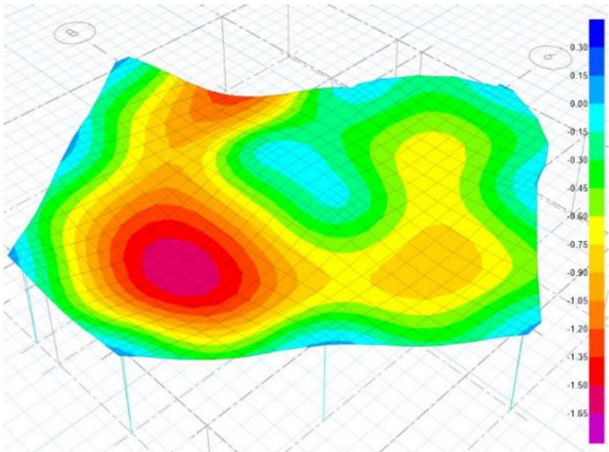
c) FS-3



d) FS-4



e) FS-5



f) FS-6

**Figure 3 :** Deflection Contours for Flat Slab Models

The results obtained from the safe software showed a good agreement with the ultimate moment and deflection value using the simplified designed method approach. Moreover the punching shear values obtained are relevant and within the range according to ACI code preventions. The results are also compared in terms of bar charts, figure-4 and 5 respectively.

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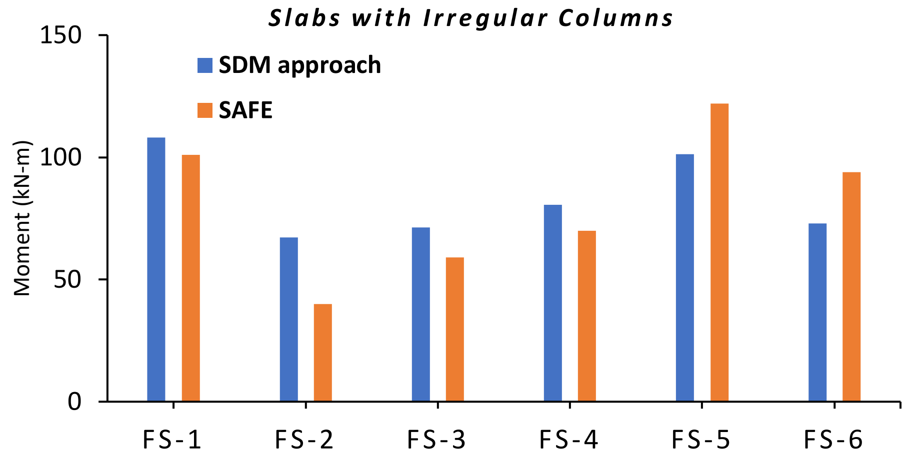


***Figure 4: Ultimate moment values comparison***

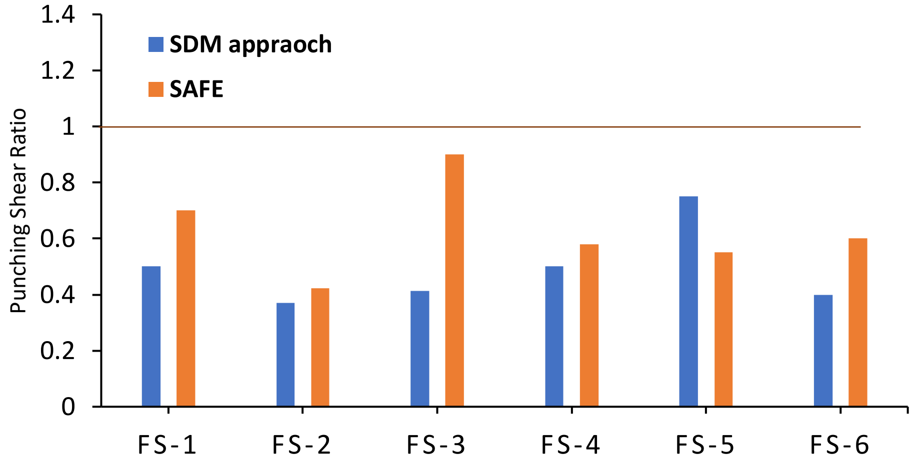


***Figure 5: Punching Shear ratio comparison***

## 4.1 NUMERICAL EXAMPLES:

***<u>SLAB FS-3</u>***

Input Data (Figure -2c):

$D.L = 0.8\ kN/m^2$

$L.L = 0.64\ kN/m^2$

D.L.F = 1.2

L.L.F= 1.6

Columns = 500 mm x 500 mm

$f_y = 400\ MPa$

$f_c' = 30\ MPa$

$E = 200{,}000\ MPa$

$\gamma_c = 25\ kN/m^3$

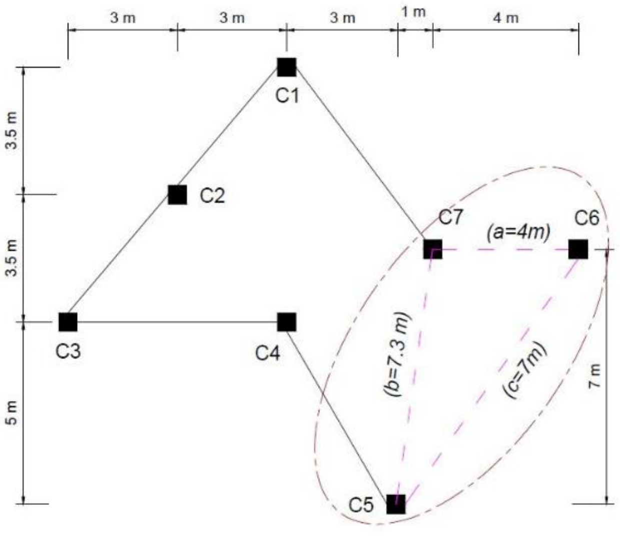


*Figure 2c: SLAB- FS-3*

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**Solution:**

**1-** Divide the slab into suitable triangles and select the triangle with the biggest span length "***L***" and linear load "***W***".

The triangular section highlighted in figure 2-c proves to be the triangle with the biggest span length ***"L"*** of **7.3 m**

**2-** Minimum slab thickness $\boldsymbol{H_{min}}$

$$H_{min} = \left({}^{L}/_{30}\right) = \left({}^{7300}/_{30}\right) = 243.3\ mm$$

$$H_{design} = 290\ mm$$

**3-** Determine Ultimate Moment $\boldsymbol{M_U}$

$$W_u = D.L.F \times \left(D.L + \frac{H_{design}}{1000} \times \gamma_c\right) + (L.L.F \times L.L)$$

$$W_u = 10.684\ kN/m^2$$

$$M_u = \frac{W_u L^2}{8} = 71.17\ kN/m$$

The design moment for this slab section is selected to be $M_{design} = 100\ kN/m$

**4-** Determine the required depth in flexure for Ultimate design Moment ($\boldsymbol{M_{design}}$).

$$k = 0.765 \times 0.375 \times \beta \times \left(1 - \frac{0.375 \times \beta}{2}\right) = 0.204$$

$$d_{flex} = \sqrt{\frac{100 \times 10^6}{0.204 \times 30 \times 1000}} = 127.52\ mm$$

$$h_{flex} = d_{flex} + d' = 157.52\ mm$$

**5-** Finding the required depth for one way shear, $\boldsymbol{V_{u(1)}}$.

$$L_p = \frac{7.3}{2} - \frac{0.5}{2} = 3.4\ mm$$

$$V_{u(1)} = W_u \times L_p = 10.684 \times 3.4 \times 1 = 36.326\ kN$$

$$36.326 = 0.75 \times {}^{1}/_{6} \times \sqrt{30} \times 1 \times (d)$$

$$d = 53.05\ mm \ \therefore\ h_{one\ way} = 53.05 + 30 = 83.05\ mm$$

**6-** Finding the two way shear depth to satisfy punching shear requirement.

$$s = \frac{1}{2}(4 + 7.3 + 7) = 9.15\ mm$$

$$A = \sqrt{s \times (s-a) \times (s-b) \times (s-c)} = 13.69\ mm^2$$

$$V_{u(2)} = A \times W_u = 146.27\ kN$$

$$r_{max} = \frac{146.27}{0.75 \times 1 \times (290 - 30) \times \left(\frac{2}{6} \times \sqrt{30}\right)}$$

$$r_{max} = 0.411 < 1\ \textit{(Safe for punching shear)}$$

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**7-** Check for the approximate deflection

$$E_c = 5000\sqrt{f_c'} = 27.38\ GPa$$

$$Moment\ of\ Inertia = I = \frac{1 \times 0.290^3}{12} = 2.032 \times 10^{-3} mm^4$$

$$W_s = \left(D.L + \frac{H_{design}}{1000} \times \gamma_c\right) + (L.L)$$

$$W_s = 8.69\ kN/m^2$$

$$M_s = \frac{W_s L^2}{8} = \ 57.886\ kN/m$$

$$\delta_{approx} = \frac{57.886}{8 \times 27.38 \times 2.032 \times 10^{-3}}\left[\left(\sqrt{7.3^2 + 7.3^2}\right) - 2 \times 0.5\right]^2 = 11.301\ mm$$

$$\delta_{approx} < \Delta_{code} = 11.301 < 20.27\ \ OK!$$

**8-** Finding the Flexural Capacity $M_c$

$$Qn = \frac{M_{design} \times 10^6}{0.9 \times 1000 \times\ (290 - 30)^2} = 1.644$$

$$\rho = \frac{0.85 \times f_c'}{f_y} \times \left(1 - \sqrt{1 - \frac{2.614 \times Qn}{f_c'}}\right) = 4.74 \times 10^{-3}$$

$$A_s = \rho \times b \times (H_{design} - d') = 1233\ mm^2$$

*Diameter of bar = 14 mm,* *Number of Bars* $N_b$ *= 9 with spacing of 120 mm.*$As_{actual} = \left(\frac{1000}{Spacing} + 1\right) \times A_b = 1437\ mm^2$

**9-** Flexural capacity $M_c = \emptyset_b A_s f_y \left(d - \frac{a}{2}\right)$

$$a = \frac{A_s f_y}{0.85 f_c' b} = \frac{1437 \times 400}{0.85 \times 30 \times 1000} = 22.54\ mm$$

$$M_c = 0.9 \times 1437 \times 400 \left(260 - \frac{22.54}{2}\right) \times 10^{-6}$$

$$M_c = 128.67\ kN.m > M_{design}\ \ (OK!)$$

**10-** Reinforcement detailing (figure-6)

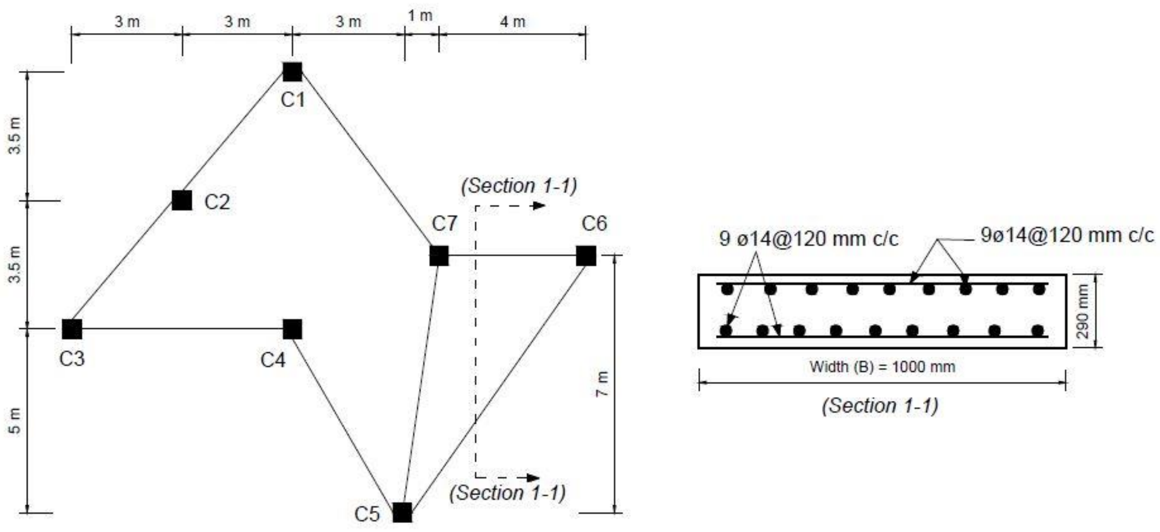


**Figure 6:** Longitudinal reinforcement section of Slab FS-3

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## 4.2 NUMERICAL EXAMPLES:

### ***SLAB FS-6***

Input Data *(Figure -2f):*

$D.L = 0.8\ kN/m^2$ ,

$L.L = 0.64\ kN/m^2$

D.L.F = 1.2

L.L.F= 1.6

Columns = 500 mm x 500 mm

$f_y = 400\ MPa$

$f_c' = 30\ MPa$

$E = 200{,}000\ MPa$

$\gamma_c = 25\ kN/m^3$

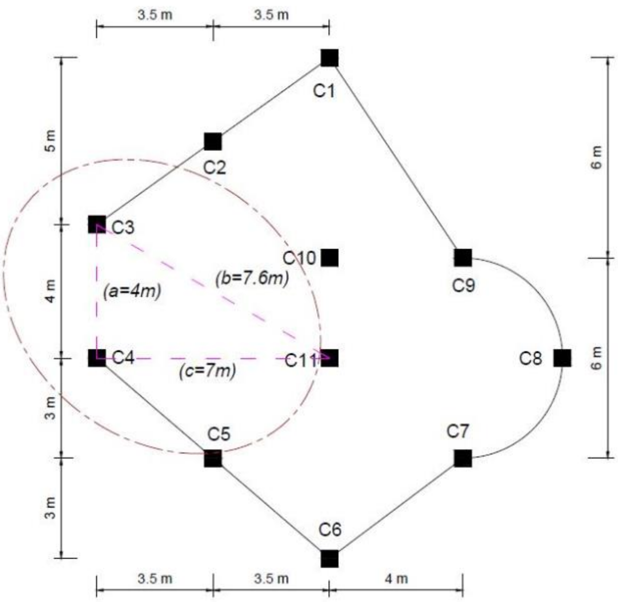


*Figure 2f: SLAB- FS-6*

**Solution:**

**1-** Divide the slab into suitable triangles and select the triangle with the biggest span length "***L***" and linear load "***W***".

The triangular section highlighted in figure *(2-f)* proves to be the triangle with the biggest span length ***"L"*** of **7.6 m**

**2-** Minimum slab thickness $\boldsymbol{H_{min}}$

$$H_{min} = \left({}^{L}/_{30}\right) = \left({}^{7600}/_{30}\right) = 253.33$$

$$H_{design} = 270\ mm$$

**3-** Determine Ultimate Moment $\boldsymbol{M_U}$

$$W_u = D.L.F \times \left(D.L + \frac{H_{design}}{1000} \times \gamma_c\right) + (L.L.F \times L.L)$$

$$W_u = 10.08\ kN/m^2$$

$$M_u = \frac{W_u L^2}{8} = \ 72.8\ kN/m$$

The design moment for this slab section is selected to be $M_{design} = 100\ kN/m$

**4-** Determine the required depth in flexure for Ultimate Moment ($\boldsymbol{M_{design}}$)**.**

$$k = 0.765 \times 0.375 \times \beta \times \left(1 - \frac{0.375 \times \beta}{2}\right) = 0.204$$

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$$d_{flex} = \sqrt{\frac{100 \times 10^6}{0.204 \times 30 \times 1000}} = 127.52\ mm$$

$$h_{flex} = d_{flex} + d' = 157.52\ mm$$

**5-** Finding the required depth for one way shear, $\boldsymbol{V_{u(1)}}$.

$$L_p = \frac{7.6}{2} - \frac{0.5}{2} = 3.55\ mm$$
$$V_{u(1)} = W_u \times L_p = 10.08 \times 3.55 \times 1 = 35.78\ kN$$
$$35.78 = 0.75 \times {}^{1}/_{6} \times \sqrt{30} \times 1 \times (d)$$

$$d = 52.26\ mm\ \therefore\ h_{one\ way} = 52.26 + 30 = 82.26\ mm$$

**6-** Finding the two way shear depth to satisfy punching shear requirement.

$$s = \frac{1}{2}(4 + 7.6 + 7) = 9.3\ mm$$
$$A = \sqrt{s \times (s-a) \times (s-b) \times (s-c)} = 13.88\ mm^2$$
$$V_{u(2)} = A \times W_u = 139.9\ kN$$
$$r_{max} = \frac{139.9}{0.75 \times 1 \times (270 - 30) \times \left(\frac{2}{6} \times \sqrt{30}\right)}$$
$$r_{max} = 0.425 < 1$$

**7-** Check for the approximate deflection

$$E_c = 5000\sqrt{f_c'} = 27.38\ GPa$$

$$Moment\ of\ Inertia = I = \frac{1 \times 0.270^3}{12} = 1.64 \times 10^{-3} mm^4$$

$$W_s = \left(D.L + \frac{H_{design}}{1000} \times \gamma_c\right) + (L.L)$$
$$W_s = 8.19\ kN/m^2$$
$$M_s = \frac{W_s L^2}{8} = 59.132\ kN/m$$
$$\delta_{approx} = \frac{59.132}{8 \times 27.38 \times 1.64 \times 10^{-3}}\left[\left(\sqrt{7.6^2 + 7.6^2}\right) - 2 \times 0.5\right]^2 = 15.64\ mm$$
$$\delta_{approx} < \Delta_{code} = 15.64 < 21.11\ \ OK!$$

**8-** Finding the Flexural Capacity $M_c$

$$Qn = \frac{M_{design} \times 10^6}{0.9 \times 1000 \times (270 - 30)^2} = 1.929$$

$$\rho = \frac{0.85 \times f_c'}{f_y} \times \left(1 - \sqrt{1 - \frac{2.614 \times Qn}{f_c'}}\right) = 5.604 \times 10^{-3}$$

$$A_s = \rho \times b \times (H_{design} - d') = 1345\ mm^2$$

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*Diameter of bar = 14 mm,* *Number of Bars $N_b$ = 9 with spacing of 120 mm.*

$$As_{actual} = \left(\frac{1000}{Spacing} + 1\right) \times A_b = 1437\ mm^2$$

**9-** Flexural capacity $M_c = \emptyset_b A_s f_y \left(d - \frac{a}{2}\right)$

$$a = \frac{A_s f_y}{0.85 f_c' b} = \frac{1437 \times 400}{0.85 \times 30 \times 1000} = 22.54\ mm$$

$$M_c = 0.9 \times 1437 \times 400 \left(240 - \frac{22.54}{2}\right) \times 10^{-6}$$

$$M_c = 118.32\ kN.m > M_{design}\ \ (OK!)$$

**10-** Reinforcement detailing (figure -7)

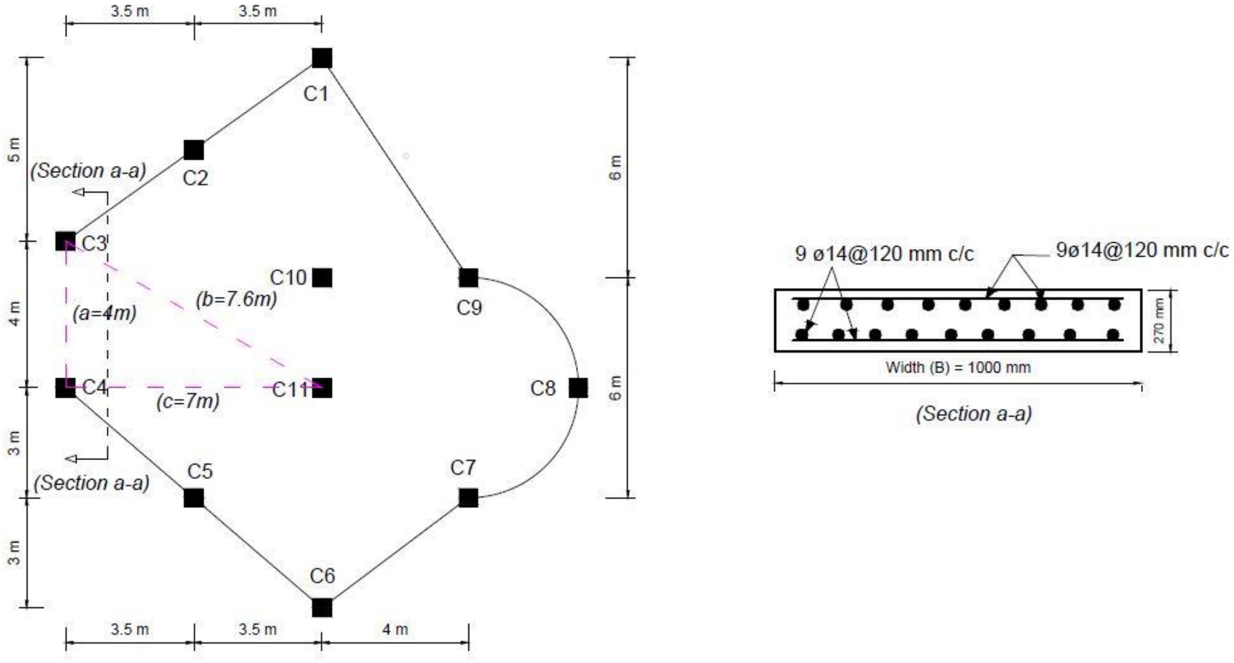


**Figure 7:** Longitudinal reinforcement section of Slab FS-6

## 5 | CONCLUSION:

In this study, a simplified method is proposed to analyse and design the flat plates with irregular column layout. These flat plates having the irregular column layout are first subdivided into triangular panels and then design the largest triangle slab panel using the ultimate-strength design method USD under the provisions of ACI building code of design (ACI 318-14).

Six different flat slabs with irregular column layouts (FS-1 to FS-6) were selected in this study to be analysed and designed using the simplified design method approach. These six slabs were also analysed and designed with computer software (SAFE). The average variation of analytically computed values to the finite element software was no more than 20% showing relatively satisfactory results. However the moment values for the SDM approach are slightly higher which makes this theoretical

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approach more conservative. Moreover the punching shear ratio obtained from the simplified design method approach is also less than < 1 for all of the studied slabs.

The obtained results indicates that the simplified design method SDM is safe, economical and quick approach to design irregular slabs sections and are also useful for the educational purposes where the students can easily analyse and design the flat slabs having the irregular column layout.

## 6 | CONFLICT OF INTEREST:

The authors declare that there is no conflict of interest regarding the publication of this article.

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