Enhancing Irregular Column Design Using Excel and VBA With a Rectangular-Parabolic Stress Block

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Abstract

A workbook with Visual Basic for Applications (VBA) has been developed and enhanced in this research by incorporating a rectangular-parabolic stress block to model concrete stress and by adding the ability to draw biaxial interaction diagrams automatically. Tension in concrete is neglected, and the stress-strain relationship in steel reinforcement is assumed to be elastic-perfectly plastic. The workbook is based on ACI 318-19 and can be used to design reinforced concrete columns in any shape, including irregular ones. The workbook contains five worksheets and six VBA subroutines. Subroutines “TestEccX” and “TestEccY” were added in this work to generate interaction diagrams of a concrete section. The capabilities of the developed workbook were demonstrated with three examples of columns with irregular shapes. The results from the workbook for hollow-square, open-box, and L-shaped columns were consistent with those from a well-known program (SpColumn). For asymmetric shapes like L-shaped columns, the difference between the results of this workbook and SpColumn (maximum difference of 6.4%) was larger than that for singly or doubly symmetric shapes (maximum difference of 3.5%). In using the workbook, initial values must be tried manually. If the initial values are far from the final results, the program may not provide an accurate solution. This was also the effect of using the GRG Nonlinear solving method in Excel, which can find only a locally optimal solution.

Keywords: *Reinforced Concrete Column, Irregular Column, Stress Block Modeling, Excel, VBA*

1. Introduction

The design of irregularly shaped columns requires considerable time and effort. Many researchers have worked to develop tools for the design of short columns with irregular shapes. Barzegar and Erasito (1995) developed worksheets to analyze RC short columns subjected to combined axial compression and biaxial bending. They assumed a rectangular stress block to compute concrete stresses. Rodriguez and Aristizabal-Ochoa (1999) presented a general method for determining the biaxial interaction diagrams. The ultimate strength of the section was expressed in closed form, and a nonlinear stress-strain relationship was employed for the concrete.

Susumpow and Line (2023) developed a workbook with VBA subroutines to calculate the capacities of reinforced concrete columns in any shape, including irregular shapes. An equivalent rectangular stress block, as typically used in the ACI Building Code, was assumed for concrete stress at the ultimate state. The maximum strain in the extreme concrete fiber is equal to 0.003. Tension in concrete is neglected. The stress-strain relationship of steel reinforcement is elastic-perfectly plastic. The results from the workbook were verified by comparing them with those from a well-known program. The results were consistent. However, a set of axial force and moment capacities can be obtained from the workbook one at a time. An interaction diagram can only be obtained by manually varying input parameters. The diagram cannot be generated automatically.

Dulinskas and Zabulionis (2007) identified inaccuracies in modeling concrete stresses, which are nonlinear, using the rectangular stress block. Their findings revealed that when the centroids of the diagrams coincide, the ratio between the areas of the nonlinear stress diagram and the rectangular stress block varies significantly, ranging from 0.103 to 1.201. They further underscore the inaccuracies in rectangular stress blocks, reinforcing the need for more precise models.

It is interesting to improve the worksheet developed by Susumpow and Line (2023). The worksheet is open, free, and can be modified without difficulty. A function to generate biaxial interaction diagrams automatically should be added. A parabolic-rectangular stress block should be used to model concrete stresses for better accuracy.

2. Objectives

The research objective is to improve the worksheet for calculating the capacities of reinforced concrete irregularly shaped columns developed by Susumpow and Line (2023) as follows:

1) Improve accuracy by using rectangular-parabolic stress blocks to model concrete stresses.
2) Expand the capabilities of the workbook to draw biaxial interaction diagrams automatically.

3. Methods

The procedure for designing of irregularly shaped reinforced concrete columns used in Susumpow and Line (2023) was reviewed. The procedure was modified by introducing a rectangular-parabolic stress block. VBA subroutines were implemented to draw biaxial interaction diagrams automatically.

3.1 Design Procedure

For a reinforced concrete column of any shape subjected to eccentric compression (N), as shown in Figure 1, the equilibrium conditions for the column can be expressed as follows:

$$N_n = \iint_{A_c} f_c(X,Y)dXdY + \sum_{j=1}^{m} f_{s_i}(X_j,Y_j)A_{s_j} \quad (1)$$

$$M_{nx} = -\iint_{A_c} Yf_c(X,Y)dXdY - \sum_{j=1}^{m} Y_j f_{s_i}(X_j,Y_j)A_{s_j} \quad (2)$$

$$M_{ny} = \iint_{A_c} Xf_c(X,Y)dXdY + \sum_{j=1}^{m} Xf_{s_i}(X_j,Y_j) \quad (3)$$

where f_c (X, Y) and A_c represent the stress distribution function and area of concrete, respectively. Signs for stress are taken as compressive stress being positive and tensile stress being negative. $f_{sj}(X_j,Y_j)$ and A_{sj} represent the stress and area of steel reinforcement, respectively, while m is the total number of reinforcements in the section.

A rectangular-parabolic stress block presented in *PCA Notes on ACI 318-11 Building Code* (Kamara, & Novak, 2013) was used to model the concrete stresses, as shown in Figure 2. Maximum concrete stress is limited to $0.85f'_c$. The maximum strain in the outermost concrete is equal to 0.003. The strain in concrete is directly proportional to the distance from the neutral axis. Tension in concrete is neglected.

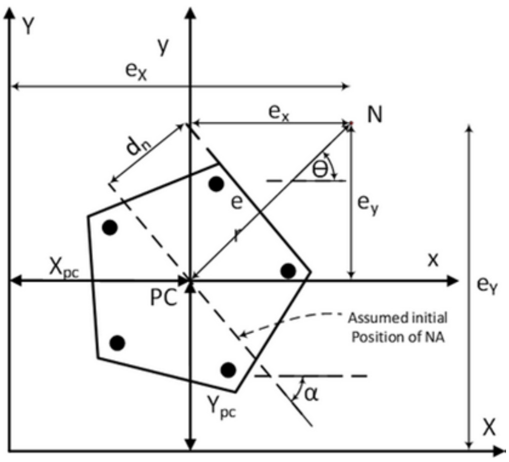

Figure 1 Column with Eccentric Loading

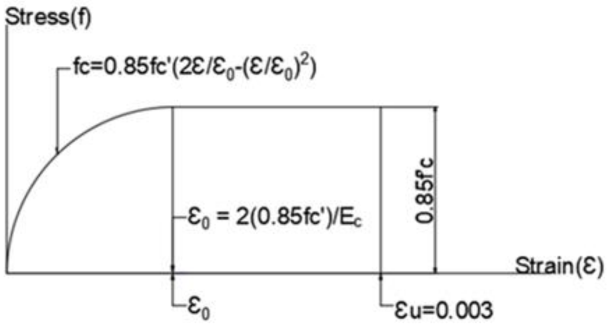

Figure 2 Details of Rectangular-Parabolic Stress Block

Equations 1 to 3 can be rewritten for the nominal capacities of the section as follows:

$$N_n = \iint_{A_{cc1}} 0.85f'_c dXdY + \iint_{A_{cc2}} 0.85f'_c \left[\frac{2\varepsilon}{\varepsilon_0} - \left(\frac{\varepsilon}{\varepsilon_0}\right)^2\right] dXdY + \sum_{j=1}^{m} f_{s_i} A_{s_j} \quad (4)$$

$$M_{nx} = -\iint_{A_{cc1}} 0.85f'_c YdXdY - \iint_{A_{cc2}} 0.85f'_c \left[\frac{2\varepsilon}{\varepsilon_0} - \left(\frac{\varepsilon}{\varepsilon_0}\right)^2\right] YdXdY - \sum_{j=1}^{m} Y_j f_{s_i} A_{s_j} \quad (5)$$

$$M_{ny} = \iint_{A_{cc1}} 0.85f'_c XdXdY + \iint_{A_{cc2}} 0.85\, f'_c \left[\frac{2\varepsilon}{\varepsilon_0} - \left(\frac{\varepsilon}{\varepsilon_0}\right)^2\right] XdXdY + \sum_{j=1}^{m} X f_{s_i} A_{s_j} \quad (6)$$

Where A_{cc1} and A_{cc2} represent the rectangular and the parabolic parts of the effective concrete area, respectively.

Considering the steel stress, the effect of strain hardening in reinforcement is neglected. The behavior of steel reinforcement in tension and compression is the same. There is perfect bonding strength between steel and concrete. The expression for steel stress (f_{sj}) is as follows:

$$f_{s_j} = E_s \varepsilon_{s_j} \quad \text{when } \varepsilon_{s_j} < \varepsilon_{s_y} \text{ and} \quad (7)$$

$$f_{s_j} = f_{sy} \quad \text{when } \varepsilon_{s_j} \geq \varepsilon_{s_y} \quad (8)$$

Where ε_{s_j} and ε_{s_y} are the strain at the location of bar j and the yield strain. E_s and f_{sy} are the modulus and yield stress of steel reinforcement, respectively.

Integration is needed to solve equations 4 to 6. To simplify the integration, the parabolic part is divided into 5 small segments with equal width (Figure 3). Green's theorem is used to find the cross-sectional area of each segment from the coordinates of boundary points (X_i and Y_i). The external and internal boundary points must be ordered in counterclockwise and clockwise directions, respectively (Figure 4). The nominal capacities (N_n, M_{nx} and M_{ny}) can be obtained as follows:

$$N_n = \sum_{k=1}^{6} \left[f_k \cdot \frac{1}{2} \sum_{i=1}^{n} a_i\right] \quad (9)$$

where $a_i = X_i Y_{i+1} - X_{i+1} Y_i$ and n is the number of points defining the boundaries of the segment. $\overline{X}$ and $\overline{Y}$ are the coordinates of the centroid of the segment. f_k is the stress at the midpoint of the width, and k is the segment number, k =where 1 to 5 for the parabolic part and k= 6 for the rectangular part.

$$M_{nx} = N_n \overline{Y} = \sum_{k=1}^{6} \left[f_k \cdot \frac{1}{6} \sum_{i=1}^{n} a_i (Y_i + Y_{i+1})\right] \quad (12)$$

$$M_{ny} = N_n \overline{X} = \sum_{k=1}^{6} \left[f_k \cdot \frac{1}{6} \sum_{i=1}^{n} a_i (X_i + X_{i+1})\right] \quad (13)$$

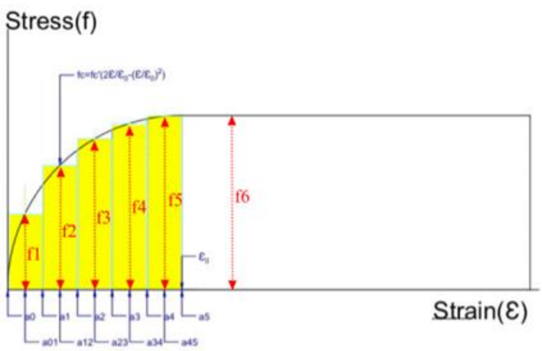

Figure 3 Simplification of the Parabolic Part by 5 Segments of Equal Width

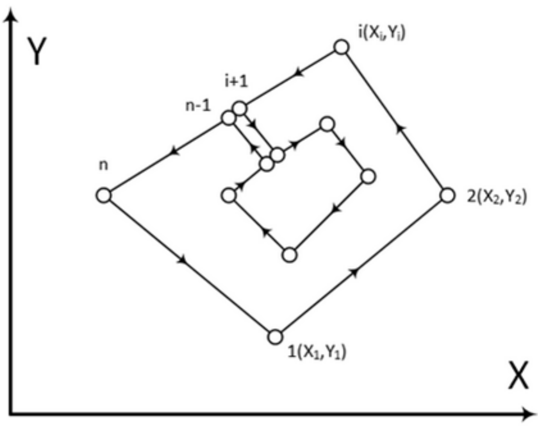

Figure 4 Numbering of Points along the Segment Boundaries

Eccentricities of load on the section are measured from the plastic centroid of the section (PC). The location of PC (X_{PC} and Y_{PC}) can be obtained from the condition where a uniform compressive stress of 0.85fc’ exists throughout the section and all steel reinforcements are under yield compression.

$$X_{PC} = \frac{0.85 f_c^{'} A \bar{X} + \sum_{j=1}^{m} X_j f_{s_i} A_{s_j}}{0.85 f_c^{'} A + \sum_{j=1}^{m} f_{s_i} A_{s_j}} \tag{14}$$

$$Y_{PC} = \frac{0.85 f_c^{'} A \bar{Y} + \sum_{j=1}^{m} Y_j f_{s_i} A_{s_j}}{0.85 f_c^{'} A + \sum_{j=1}^{m} f_{s_i} A_{s_j}} \tag{15}$$

To obtain a nominal axial force at a set of required eccentricities (e_x and e_y), the boundaries of a particular cross-section and the reinforcement locations shall be input. The plastic centroid (PC) of the section shall be calculated. Assume the location and orientation of the neutral axis of the section. Calculate the nominal capacities of the section (N_n, M_{nx} and M_{ny}) and the resulting eccentricities (e_{nx} and e_{ny}). Check the difference between the required eccentricities and the resulting eccentricities. If the difference is noticeable, re-assume the location and orientation of the neutral axis and recalculate until the difference is nearly zero.

A set of design strengths for the section is then obtained by multiplying the nominal capacities with an appropriate strength reduction factor. The strength reduction factor is taken from Table 21.2.2 of ACI 318-99 (ACI Committee 318, 2019), as shown in Equation 16. Other sets of design strengths can be obtained by a similar procedure. The interaction diagram can finally be generated from these sets of design strengths.

$$\phi = \begin{cases} 0.65 & \text{when} \quad \varepsilon_t \leq \varepsilon_{ty} \text{ (Compression Controlled)} \\ 0.65+0.25\frac{(\varepsilon_t-\varepsilon_{ty})}{0.003} & \text{when} \quad \varepsilon_{ty} < \varepsilon_t < \varepsilon_{ty} + 0.003 \text{ (Transition)} \\ 0.9 & \text{when} \quad \varepsilon_t \geq \varepsilon_{ty} + 0.003 \text{ (Tension Controlled)} \end{cases} \quad (16)$$

3.2 Program Development

An Excel workbook developed in this research was adapted from the workbook developed by Susumpow and Line (2023). An illustrating of the development is shown in Figure 5. The parts of the workbook developed before were explained briefly here as a basis. In this research, the concrete stresses were modeled as a rectangular-parabolic stress block instead of the rectangular stress block previously used. Moreover, VBA subroutines were added to draw biaxial interaction diagrams automatically. These subjects were explained in detail.

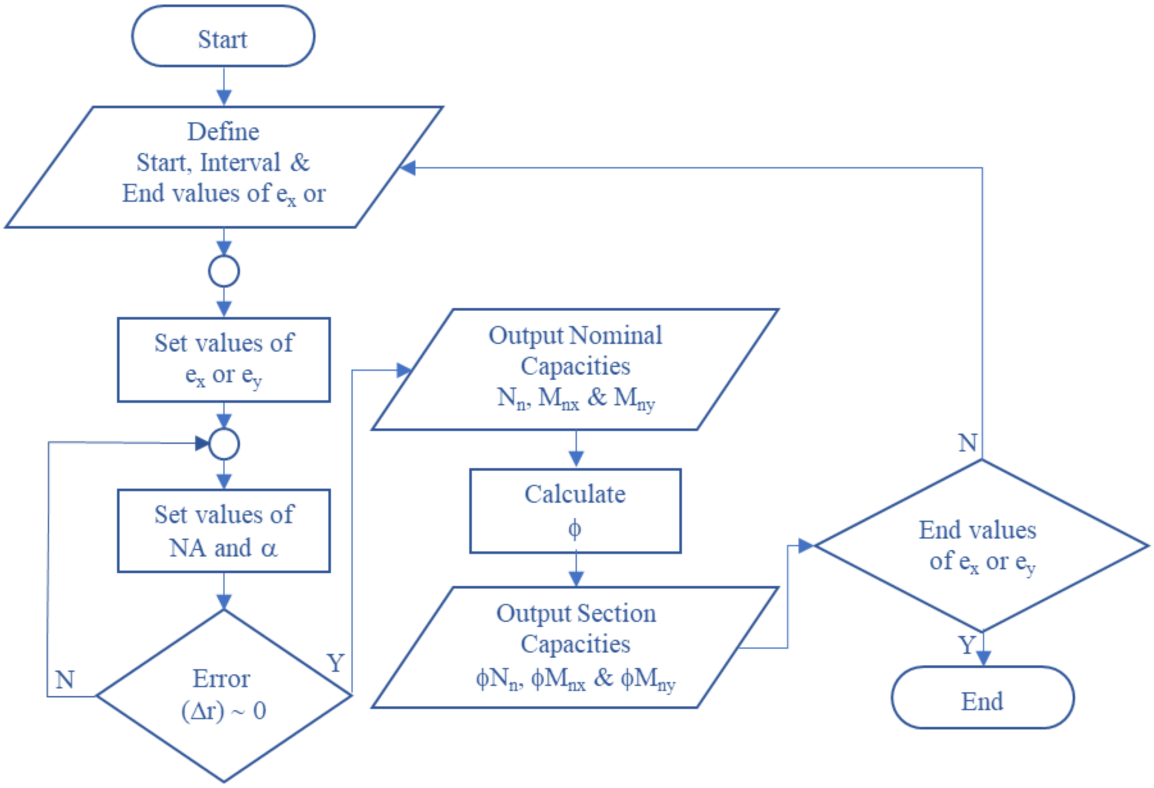

Figure 5 Flowchart of the Developed Workbook

This workbook contains 5 worksheets, namely “input”, “calculation”, “figure”, “EccX”, and “EccY”. Worksheet “input” includes all necessary input data, such as the cross-section boundary coordinates, steel yield stress, total number and position of reinforcements, the size of rebar, and the compressive strength of concrete. This program was designed to input up to 100 reinforcing bars and 100 boundary points.

Worksheet “calculation” utilizes the data from the first worksheet to generate design strengths of the section. This worksheet is divided into 3 sub-parts, such as Parts A, B, and C (Figure 6). Part A (Figure 7) displays a review of important data input. By pressing the button “Run”, the worksheet will try a series of values for the neutral axis depth and angle of inclination until calculation error is negligible. Then, the nominal axial load and bending moments on both axes are shown. Part B consists of calculations regarding stresses and bending moments of concrete under compression using the concept of a parabolic-rectangular stress block (Figure 8). The calculation of compressive force involves determining the forces under the rectangular and parabolic stress blocks (5 segments with equal width). All forces in the calculation are shown in Figure 9.

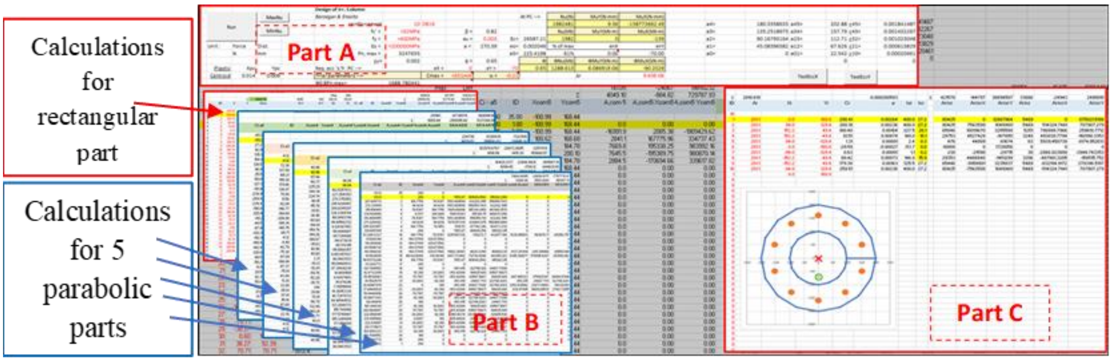

Figure 6 Overview of Worksheet "calculation"

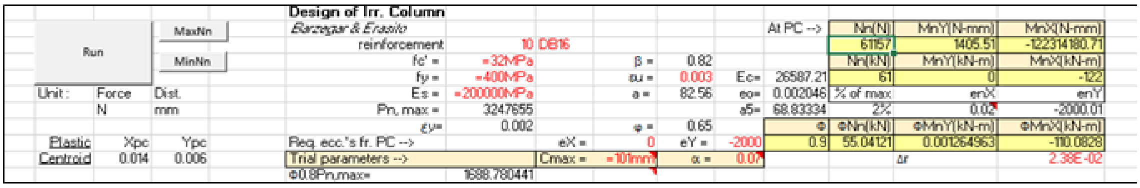

Figure 7 Part A of Worksheet "calculation"

Part C (Figure 10) determines the axial force and moments created by reinforcements. Stress in reinforcement was modeled as an elastic-perfectly plastic material. When the strain in reinforcement is less than the yield strain, the reinforcement behaves like an elastic material. However, the stress in reinforcement will equal to the yield stress when the strain is greater than the yield strain.

Worksheet "figure" stores coordinates of column boundaries and rebar locations in a sequential order and presents a picture of the cross-section along with the rebar's location. Worksheets "EccX" and "EccY" store results from executing VBA Subroutines "TestEccX" and "TestEccY", respectively (Figures 11 and 12). The results are eccentricities (eX and eY), nominal capacities (Nn, MnX and MnY), calculation error (error), and design strengths (phiNn, phiMnX and phiMnY. Interaction diagrams are then generated from these results (Figures 13 and 14).

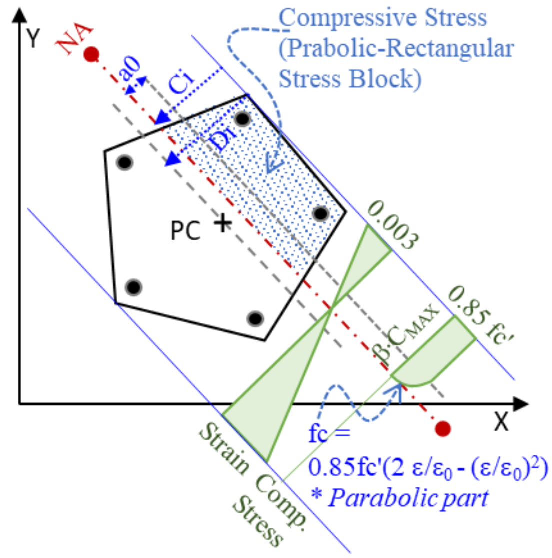

Figure 8 Compressive Stress-Strain Relation of Parabolic-Rectangular Stress Block

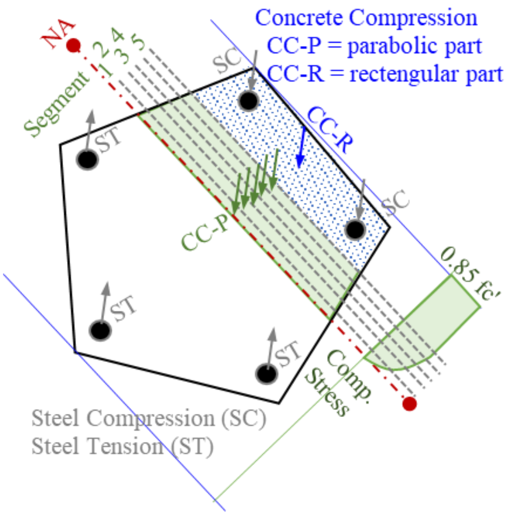

Figure 9 Compressive and Tensile Forces in Calculations

Σ	14476.459				-0.002970144			Σ	-1092701	22182636	764009305	121403	1812319	22851856
ID	Ai	Xi	Yi	Ci	εi	fsi	fci		Ai·fsi	Ai·fsi·X	Ai·fsi·Y	Ai·fci	Ai·fci·X	Ai·fci·Y
18														
1	804.2	146.0	-254.0	-207.05	-0.00179	-357.1	0.0		-287188	-41929422	72945707	0	0	0
2	804.2	46.0	-254.0	-252.84	-0.00218	-400.0	0.0		-321699	-14798158	81711568	0	0	0
3	804.2	-54.0	-254.0	-298.64	-0.00258	-400.0	0.0		-321699	17371751	81711568	0	0	0
4	804.2	-154.0	-254.0	-344.43	-0.00297	-400.0	0.0		-321699	49541660	81711568	0	0	0
5	804.2	-154.0	-154.0	-255.53	-0.00220	-400.0	0.0		-321699	49541660	49541660	0	0	0
6	804.2	-154.0	-54.0	-166.63	-0.00144	-287.4	0.0		-231132	35594352	12481137	0	0	0
7	804.2	-154.0	46.0	-77.74	-0.00067	-134.1	0.0		-107825	16605058	-4959952	0	0	0
8	804.2	-154.0	146.0	11.16	0.00010	19.3	2.2		15482	-2384237	2260381	1771	-272692.9263	258527.06
9	804.2	-154.0	246.0	100.06	0.00086	172.6	21.3		138789	-21373532	34142136	17090	-2631900.661	4204204.953

Figure 10 Part C of Worksheet “calculation”

eX	eY	Nu(kN)	MuX(kN-m)	MuY(kN-m)	error	phi	phiNu(KN)	phiMuX(kN-m)	phiMuY(kN-m)	Cmax	inclination
									0		
20	0	7242.813	0.039218593	144.8782557	0.006209	0.65	4707.828167	0.025492086	94.17086618	855.5653	-89.07320526
40	0	6587.621	0.057429782	263.5339062	0.00977	0.65	4281.953803	0.037329358	171.297039	694.198	-89.18567905
60	0	6020.073	0.005358881	361.2072865	0.001012	0.65	3913.04753	0.003483272	234.7847362	619.9972	-85.41809798
80	0	5541.372	0.000592146	443.309773	0.000107	0.65	3601.892001	0.000384895	288.1513524	568.792	-84.75866191
100	0	5138.734	0.001056361	513.8736476	0.000213	0.65	3340.176899	0.000686634	334.017871	528.3742	-85.99338535
120	0	4750.409	1.737253038	573.2326506	0.76345	0.65	3087.766025	1.129214474	372.6012229	497.7595	-84.85197201
140	0	4483.597	-12.70612067	614.0937459	4.15273	0.65	2914.338116	-8.258978438	399.1609348	497.9895	-84.86011759
160	0	4146.466	0.004274127	663.4349283	0.001035	0.65	2695.202817	0.002778183	431.2327034	445.5525	-85.15544894
180	0	3894.704	0.000219003	701.0469022	8.78E-05	0.65	2531.557309	0.000142352	455.6804864	420.3236	-85.98135776
200	0	3665.764	0.004624371	733.1531246	0.001266	0.65	2382.746361	0.003005841	476.549531	401.16	-86.19294386

Figure 11 Overview of Worksheet “EccX”

eX	eY	Nu(kN)	MuX(kN-m)	MuY(kN-m)	error	phi	phiNu(KN)	phiMuX(kN-m)	phiMuY(kN-m)	Cmax
								0		
0	-20	7124.649	-142.4940828	0.001249097	0.000233	0.65	4631.022167	-92.6211538	0.000811913	795.8052
0	-40	6345.538	-253.8216318	0.000728814	0.000117	0.65	4124.599385	-164.9840606	0.000473729	643.3442
0	-60	5696.07	-341.7643269	0.001930061	0.00034	0.65	3702.445277	-222.1468125	0.00125454	565.5017
0	-80	5170.49	-413.63809	0.000714589	0.000261	0.65	3360.818779	-268.8647585	0.000464483	520.1385
0	-100	4710.381	-471.0391755	-0.000279695	0.000235	0.65	3061.747694	-306.1754641	-0.000181802	485.9213
0	-120	4299.29	-515.9165166	0.00053261	0.000422	0.65	2794.538397	-335.3457358	0.000346197	455.434
0	-140	3953.072	-553.4305936	0.001210236	0.000328	0.65	2569.497012	-359.7298858	0.000786654	431.8079
0	-160	3647.045	-583.5283565	0.005346643	0.001504	0.65	2370.578988	-379.2934318	0.003475318	409.1093
0	-180	3382.56	-608.8610859	0.000873158	0.000277	0.65	2198.663811	-395.7597058	0.000567552	392.516
0	-200	3150.633	-630.1268951	0.000863627	0.000296	0.65	2047.91126	-409.5824818	0.000561358	378.0419

Figure 12 Overview of Worksheet “EccY”

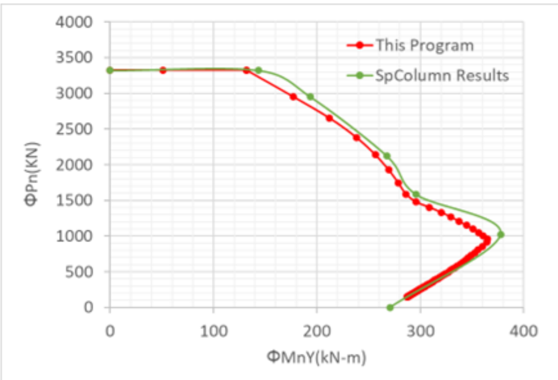

Figure 13 Sample Interaction Diagram for X-Eccentricity

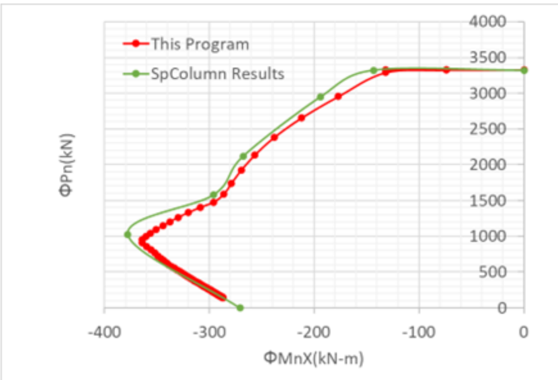

Figure 14 Sample Interaction Diagram for Y-Eccentricity

There are six main VBA subroutines with six corresponding macro buttons in the workbook. Subroutines "clear","RUN", "MaxNn", "MinNn" perform the same tasks as in the workbook of Susumpow and Line (2023). Subroutines "TestEccX" and "TestEccY" can be activated by using buttons of the same names in the Worksheet "calculation". Details of Subroutine "TestEccX" are shown in Figure 15. First, the initial depth of the neutral axis (NA) and the inclination angle of the neutral axis (α) are defined. Subroutine "RUN" is then called. This subroutine has Function "SolverOk" which will try to minimize error and get correct values of NA and α. The function is set to use the GRG Nonlinear solving method, which can find a locally optimal solution. Column "error" in Worksheet "EccX" and "EccY" shall be checked carefully since sometimes the function cannot get a proper result. In some cases. Initial values of NA and α have to be modified so that a proper result can be obtained. Other sets of design strengths will be found by changing the eccentricity in the X or Y direction using a looping command with a similar procedure. Finally, an interaction diagram can be created from all sets of the design strengths. Subroutine "TestEccY" has a similar structure as Subroutine "TestEccX" and is not explained here.

4. Results and Discussion

In this section, the ability of this developed workbook to generate interaction diagrams of any shaped reinforced concrete columns was demonstrated. Three examples were tested, i.e., Hollow-Square, Open-Box, and L-shaped columns. The results were compared to those of a well-known program, SpColumn (SPC) by StructurePoint (2021). Details of the investigations are shown in the following.

```
Sub TestEccX()
'
' Find solution by varying EccX

'
    Sheets("EccX").Cells.clear
    Sheets("calculation").Cells(10, 9) = 800
    Sheets("calculation").Cells(11, 9) = 20
    Sheets("calculation").Cells(9, 11) = 0
    For xi = 1 To 100
      Sheets("calculation").Cells(9, 9) = 20 * xi
      Sheets("EccX").Cells(2 + xi, 1) = 20 * xi
      Call RUN
      Sheets("EccX").Cells(1, 1).Value = "eX"
      Sheets("EccX").Cells(1, 2).Value = "eY"
      Sheets("EccX").Cells(1, 3).Value = "Nu(kN)"
      Sheets("EccX").Cells(1, 4).Value = "MuX(kN-m)"
      Sheets("EccX").Cells(1, 5).Value = "MuY(kN-m)"
      Sheets("EccX").Cells(1, 6).Value = "error"
      Sheets("EccX").Cells(1, 7).Value = "phi"
      Sheets("EccX").Cells(1, 8).Value = "phiNu(KN)"
      Sheets("EccX").Cells(1, 9).Value = "phiMuX(kN-m)"
      Sheets("EccX").Cells(1, 10).Value = "phiMuY(kN-m)"
      Sheets("EccX").Cells(1, 11).Value = "Cmax"
      Sheets("EccX").Cells(1, 12).Value = "inclination"
      Sheets("EccX").Cells(1, 13).Value = "Reinforcement closest to tension face"
      Sheets("EccX").Cells(2 + xi, 2) = Sheets("calculation").Cells(9, 11)
      Sheets("EccX").Cells(2 + xi, 3) = Sheets("calculation").Cells(5, 13)
      Sheets("EccX").Cells(2 + xi, 4) = Sheets("calculation").Cells(5, 15)
      Sheets("EccX").Cells(2 + xi, 5) = Sheets("calculation").Cells(5, 14)
      Sheets("EccX").Cells(2 + xi, 6) = Sheets("calculation").Cells(10, 15)
      Sheets("EccX").Cells(2 + xi, 7) = Sheets("calculation").Cells(9, 12)
      Sheets("EccX").Cells(2 + xi, 8) = Sheets("calculation").Cells(9, 13)
      Sheets("EccX").Cells(2 + xi, 9) = Sheets("calculation").Cells(9, 15)
      Sheets("EccX").Cells(2, 10) = 0
      Sheets("EccX").Cells(2 + xi, 10) = Sheets("calculation").Cells(9, 14)
      Sheets("EccX").Cells(2 + xi, 11) = Sheets("calculation").Cells(10, 9)
      Sheets("EccX").Cells(2 + xi, 12) = Sheets("calculation").Cells(10, 11)
      Sheets("EccX").Cells(2 + xi, 13) = Sheets("calculation").Cells(13, 74)
      Sheets("EccX").Cells(1 + xi, 17) = Sheets("calculation").Cells(11, 7)
    Next xi
End Sub
```

```
Sub RUN()
    SolverOk SetCell:="$O$10", MaxMinVal:=2, _
        ValueOf:=0, ByChange:="$I$10:$I$11", _
        Engine:=1, EngineDesc:="GRG Nonlinear"
'    SolverSolve
    SolverSolve (True)
End Sub
```

Figure 15 VBA Subroutines "TestEccX" and "RUN"

4.1 Hollow-Square Column

In this example, a Hollow-Square column with 450x450 mm dimensions and a 150x150 mm internal void reinforced by 20 DB16 was investigated in this example (Figure 16). The concrete and steel strengths were 32 MPa and 400 MPa, respectively. Figure 17 shows that the interaction diagrams for X and Y-axes eccentricities obtained from the workbook were consistent with those from SpColumn. Differences in results from this program and from SPC are shown in Table 1. The maximum difference in moment capacities is 3.5%, while that in axial force capacities is 0.1%.

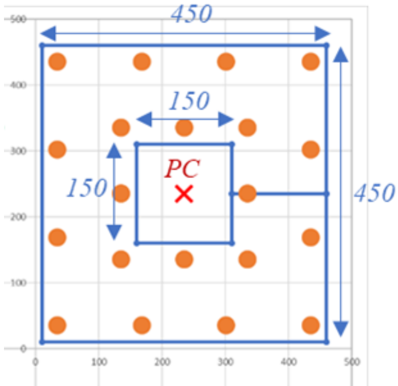

Figure 16 Hollow-Square Column Cross-section and Reinforcements

Table 1 Differences in Results from This Program and from SPC in the Case of Hollow-Square Column

Point to Compare		This Prog.	SPC	Diff.
Y Eccen.	Max. M	364.6	377.6	-3.4%
	Max. N	3325.5	3321.3	0.1%
X Eccen.	Max. M	-364.2	-377.6	-3.5%
	Max. N	3325.5	3321.3	0.1%

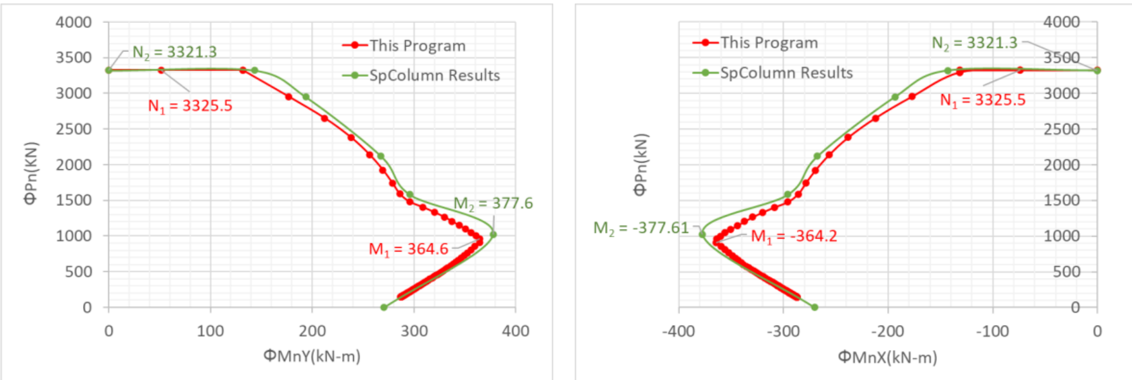

Figure 17 Interaction Diagrams for X and Y-axes Eccentricities (Hollow-Square Column)

4.2 Open-Box Column

An Open-Box column with 500x500 mm dimensions and a 300x300 mm internal void reinforced by 56 DB16 was investigated in this example (Figure 18). The concrete and steel strengths were 32 MPa and 400 MPa, respectively. Figure 19 shows that the interaction diagrams for X and Y-axes eccentricities obtained from the workbook were consistent with those from sPColumn. The results also demonstrate the efficiency of the workbook to analyze such a similar section to a lift core. Differences in results from this program and from SPC are shown in Table 2. The maximum difference in moment capacities is 1.2%, while that in axial force capacities is 0.3%.

4.3 L-shaped Column

An L-shaped column with maximum dimensions of 500 x 700 mm and reinforced by 18 DB32 was investigated in this example. The concrete and steel strengths were 25 MPa and 400 MPa, respectively (Figure 20). Figure 21 shows that the interaction diagrams for X and Y-axes eccentricities obtained from the workbook were quite similar to those from sPColumn. However, the difference between the results of this workbook and sPColumn is larger than in other examples. Differences in results from this program and from SPC are shown in Table 3. The maximum difference in moment capacities is 6.4%, while that in axial force capacities is 0.9%.

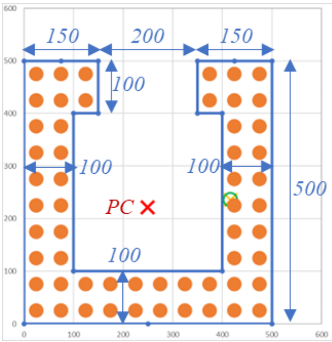

Figure 18 Open-Box Column Cross-section and Reinforcements

Table 2 Differences in Results from This Program and from SPC in the Case of Open-Box Column

Point to Compare		This Prog.	SPC	Diff.
Y Eccen.	Max. M	868.1	875.3	-0.8%
	Max. N	4162.9	4151.3	0.3%
X Eccen.	Max. M	-584.9	-592.2	-1.2%
	Max. N	4162.9	4151.4	0.3%

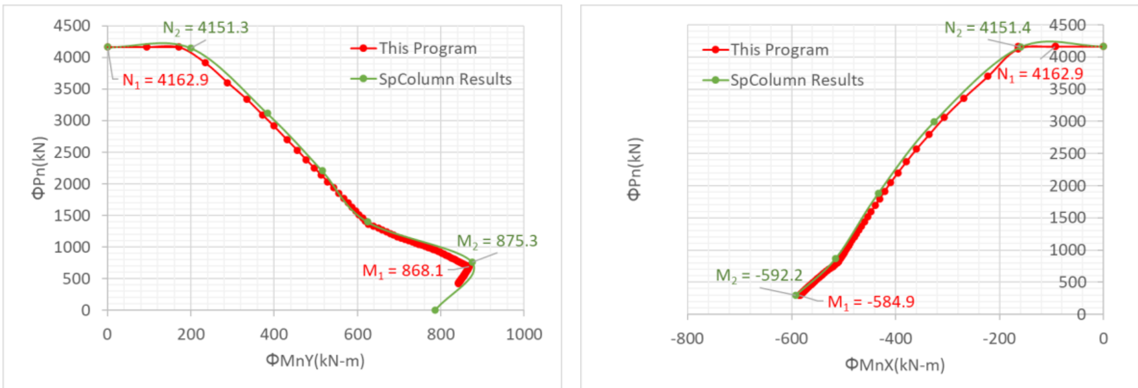

Figure 19 Interaction Diagrams for X and Y-axes Eccentricities (Open-Box Column)

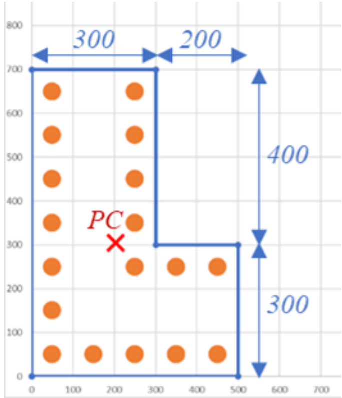

Figure 20 L-shaped Column Cross-section and Reinforcements

Table 3 Differences in Results from This Program and from SPC in the Case of L-shaped Column

Point to Compare		This Prog.	SPC	Diff.
Y Eccen.	Max. M	558.1	565.8	-1.4%
	Max. N	5834.6	5888.2	-0.9%
X Eccen.	Max. M	-859.6	-918.8	-6.4%
	Max. N	5834.6	5888.2	-0.9%

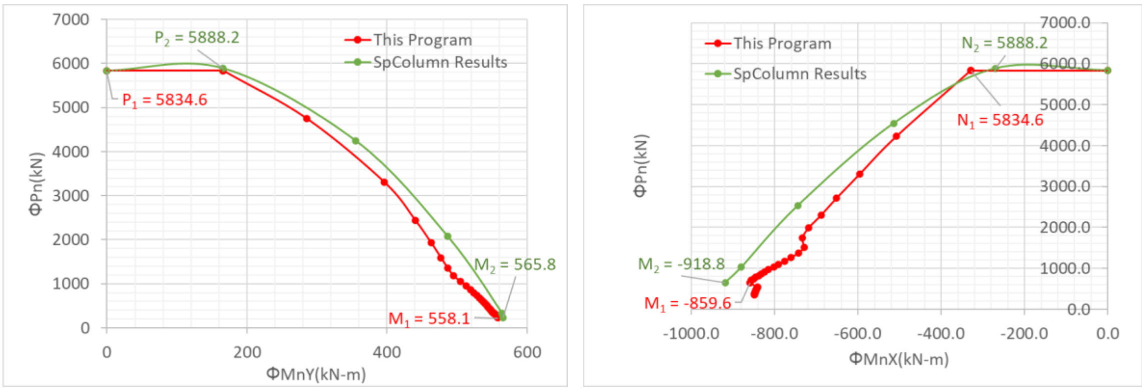

Figure 21 Interaction Diagrams for X and Y-axes Eccentricities (L-shaped Column)

In using the current workbook, initial values have to be tried. For an asymmetric shape like an L-shaped column, it was more difficult to obtain proper initial values, and this resulted in a greater percentage of difference. Improvement on this issue using advanced tools such as machine learning shall be done in the future.

5. Conclusion

A workbook with VBA had been developed by Susumpow and Line (2023) was enhanced by incorporating the rectangular-parabolic stress block to model concrete stress at the ultimate state and by adding the ability to draw biaxial interaction diagrams automatically. As employed in the previous work, tension in concrete is neglected, and the stress-strain relationship in steel reinforcement is elastic-perfectly plastic. The workbook can be used to design reinforced concrete columns in any shape, including irregular shapes. The workbook contains five worksheets and six VBA subroutines. Subroutines “TestEccX” and “TestEccY” were added in this work to generate design strengths at various eccentricities of force, and interaction diagrams can be obtained. The abilities of the developed workbook were demonstrated with three examples of columns with irregular shapes. The results from the workbook for hollow-square, open-box, and L-shaped columns were consistent with those from a well-known program. However, the difference between the results for the L-shaped column (asymmetric shape) was larger than that of the other shapes (singly or doubly symmetric shape). In the case of hollow-square and open-box sections, the maximum difference in moment capacities is 3.5%, while that in axial force capacities is 0.3%. In the case of the L-shaped column section, the maximum difference in moment capacities is 6.4%, while that in axial force capacities is 0.9%. The use of proper initial values is important. The values have to be tried manually. If the initial values are far from the final results, the program may not provide an accurate solution. An ability to automatically set initial values should be added to the workbook using some advanced tools such as machine learning. Also, the solving method should be improved so that final results can be obtained even if the assumed initial values are far away.

6. References

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