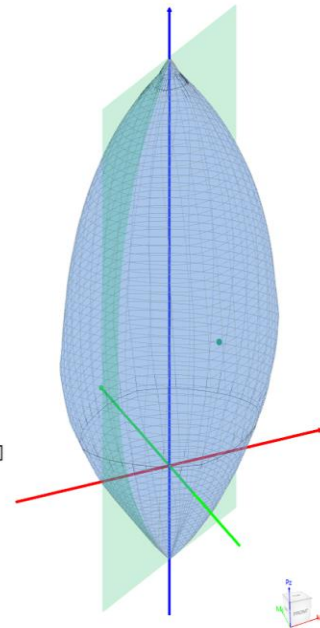
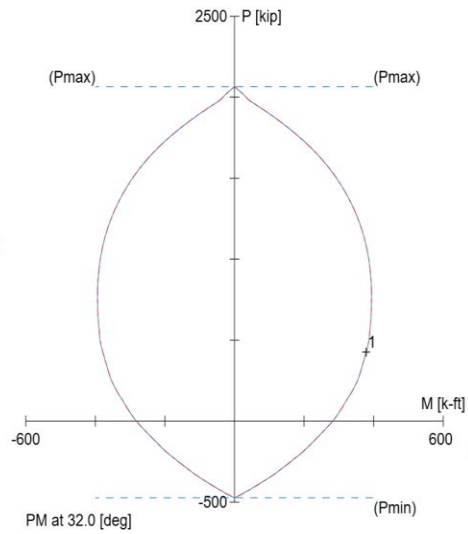
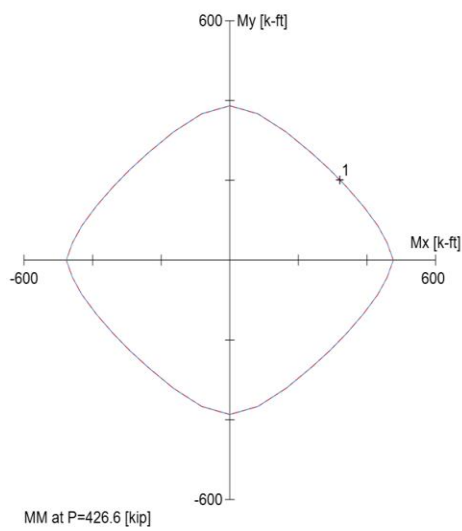
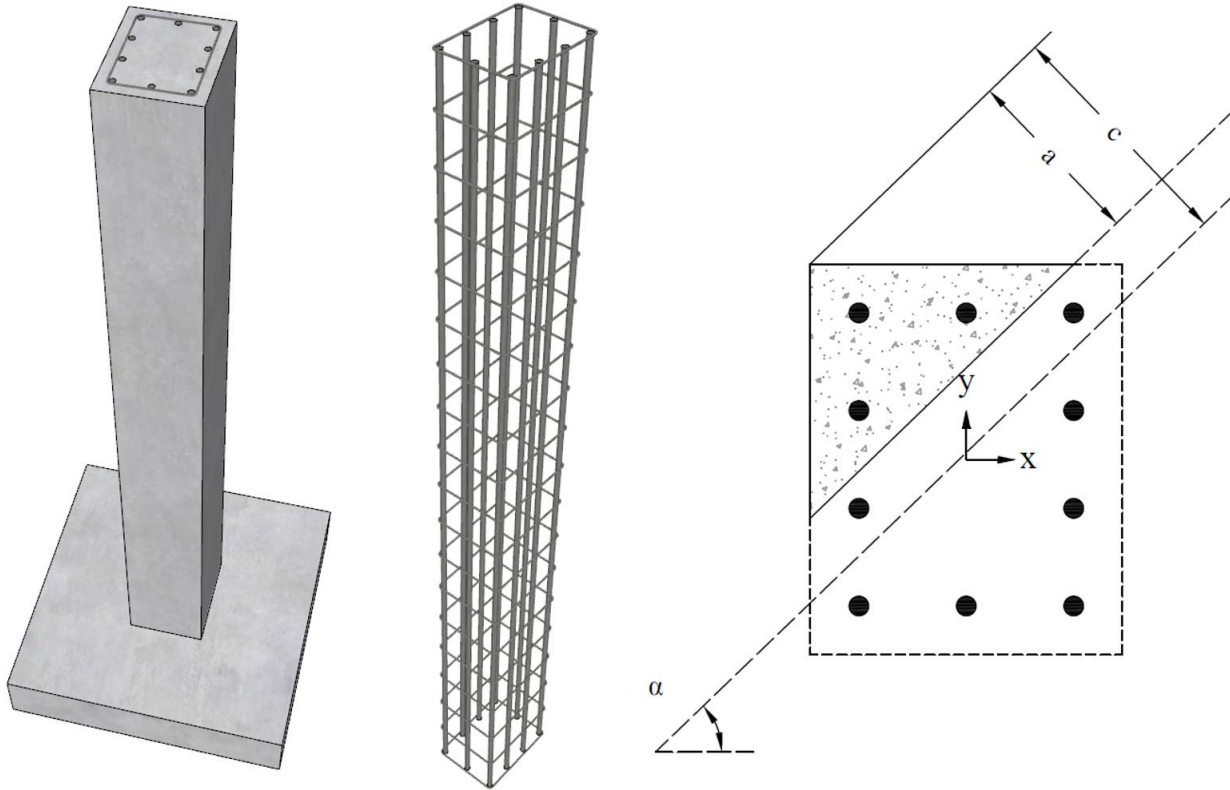


Biaxial Bending Interaction Diagrams for Rectangular Reinforced Concrete Column Design (ACI 318-19)



Biaxial Bending Interaction Diagrams for Rectangular Reinforced Concrete Column Design (ACI 318-19)

Biaxial bending of columns occurs when the loading causes bending simultaneously about both principal axes. The commonly encountered case of such loading occurs in corner columns. Corner and other columns exposed to known moments about each axis simultaneously should be designed for biaxial bending and axial load.

A uniaxial interaction diagram defines the load-moment strength along a single plane of a section under an axial load P and a uniaxial moment M . The biaxial bending resistance of an axially loaded column can be represented schematically as a surface formed by a series of uniaxial interaction curves drawn radially from the P axis. Data for these intermediate curves are obtained by varying the angle of the neutral axis (for assumed strain configurations) with respect to the major axes.

The difficulty associated with the determination of the strength of reinforced columns subjected to combined axial load and biaxial bending is primarily an arithmetic one. The bending resistance of an axially loaded column about a particular skewed axis is determined through iterations involving simple but lengthy calculations. These extensive calculations are compounded when optimization of the reinforcement or cross-section is sought.

This example demonstrates the determination of the biaxial flexural strength of a rectangular reinforced concrete column at a particular nominal axial strength ($P_n = 426$ kips) with a moment ratio of biaxial bending moments in the X and Y direction ($M_{nx}/M_{ny} = 1.60$). The figure below shows the reinforced concrete rectangular column cross section in consideration. The calculated values of the column biaxial bending strength are compared with the values from the reference and the exact values from [spColumn](#) engineering software program from [StructurePoint](#). The steps to develop the three-dimensional failure surface (interaction diagram) using [spColumn](#) will be shown in detail as well.

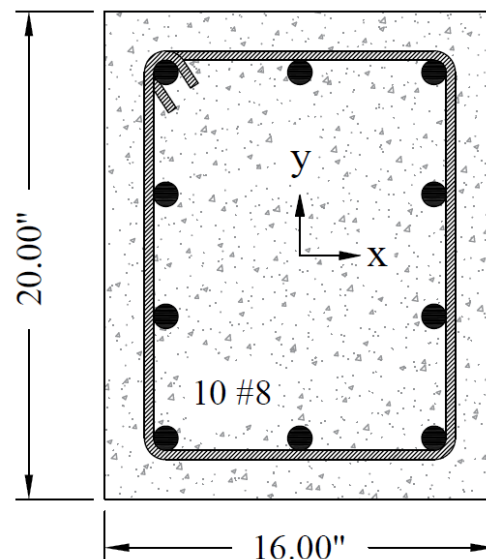


Figure 1 – Reinforced Concrete Column Cross-Section

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Code

Building Code Requirements for Structural Concrete (ACI 318-19) and Commentary (ACI 318R-19)

References

- Reinforced Concrete Design, 9th Edition, 2021, Pincheira J. et. al., Oxford University Press, Example 10.20.1
- Notes on ACI 318-11 Building Code Requirements for Structural Concrete, Twelfth Edition, 2013 Portland Cement Association
- [spColumn Engineering Software Program Manual v10.00, STRUCTUREPOINT, 2021](#)
- [“Biaxial Bending Interaction Diagrams for Square Reinforced Concrete Column Design \(ACI 318-19\)”](#) Design Example, [STRUCTUREPOINT, 2022](#)
- [“Biaxial Bending Interaction Diagrams for C-Shaped Concrete Core Wall Design \(ACI 318-19\)”](#) Design Example, [STRUCTUREPOINT, 2022](#)
- [“Biaxial Bending Interaction Diagrams for Spiral Reinforced Circular Concrete Column Design \(ACI 318-19\)”](#) Design Example, [STRUCTUREPOINT, 2022](#)
- [“Manual Design Procedure for Columns and Walls with Biaxial Bending \(ACI 318-11/14/19\)”](#) Design Example, [STRUCTUREPOINT, 2022](#)

Design Data

$$f_c' = 6000 \text{ psi}$$

$$f_y = 60000 \text{ psi}$$

Cover = 2.5 in.

Column dimensions and reinforcement locations are shown in following figure.

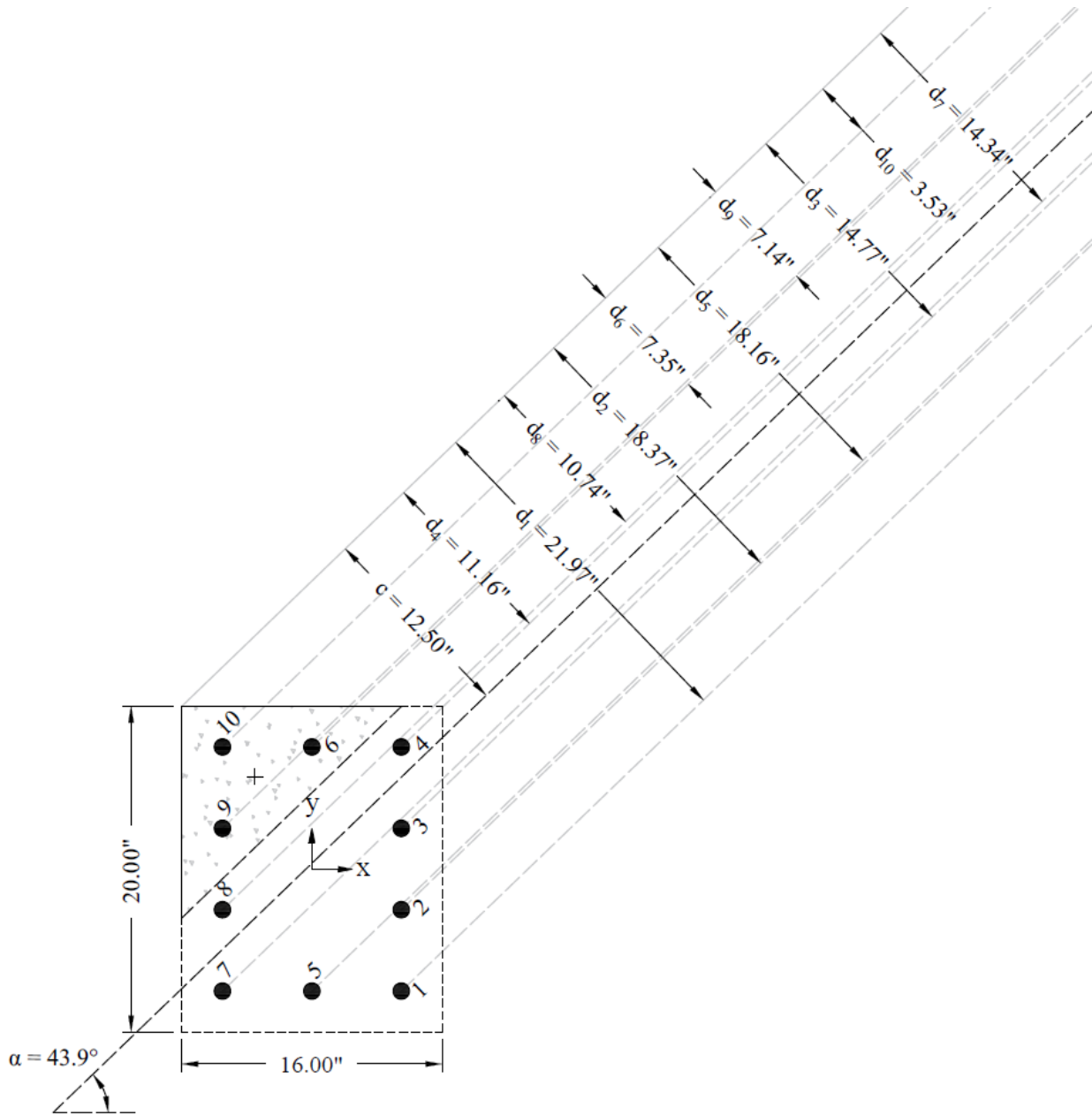


Figure 2 – Reinforced Concrete Column Cross-Section and Reinforcement Locations

Solution

In a reinforced concrete column, the determination of biaxial moment strength for a given axial force involves a trial-and-error process for calculating the neutral axis depth and angle α (Figure 2). The reference shows that using this process for the given column section leads to a value of the neutral axis depth of $c = 12.5$ in. and an angle of $\alpha = 43.9^\circ$. In this example the last iteration will be shown for illustration of the procedure as a representative calculation of the complete trial and error procedure.

The steps to calculate biaxial flexural strength of a rectangular reinforced concrete column for a given nominal axial strength and moment ratio of biaxial bending moments are as follows:

1. Assuming a value for the angle of the neutral axis (α) and the neutral axis depth (c) and calculating the strain values in each reinforcement layer
2. Calculating the forces values in the concrete (C_c) and reinforcement layers (F_{si})
3. Calculating P_n and M_{nx}/M_{ny} using the following equations

$$P_n = C_c + \sum F_s$$

$$M_{ny} = C_c \times \left(\frac{b}{2} - \bar{x}_c \right) + \sum_{i=1}^{n=10} \left(F_{si} \times \left(\frac{b}{2} - x_i \right) \right)$$

$$M_{nx} = C_c \times \left(\frac{h}{2} - \bar{y}_c \right) + \sum_{i=1}^{n=10} \left(F_{si} \times \left(\frac{h}{2} - y_i \right) \right)$$

The procedure above should be repeated until the calculated P_n , and M_{nx}/M_{ny} are equal to the given P_n , and M_{nx}/M_{ny} . The following figure demonstrates the procedure explained above:

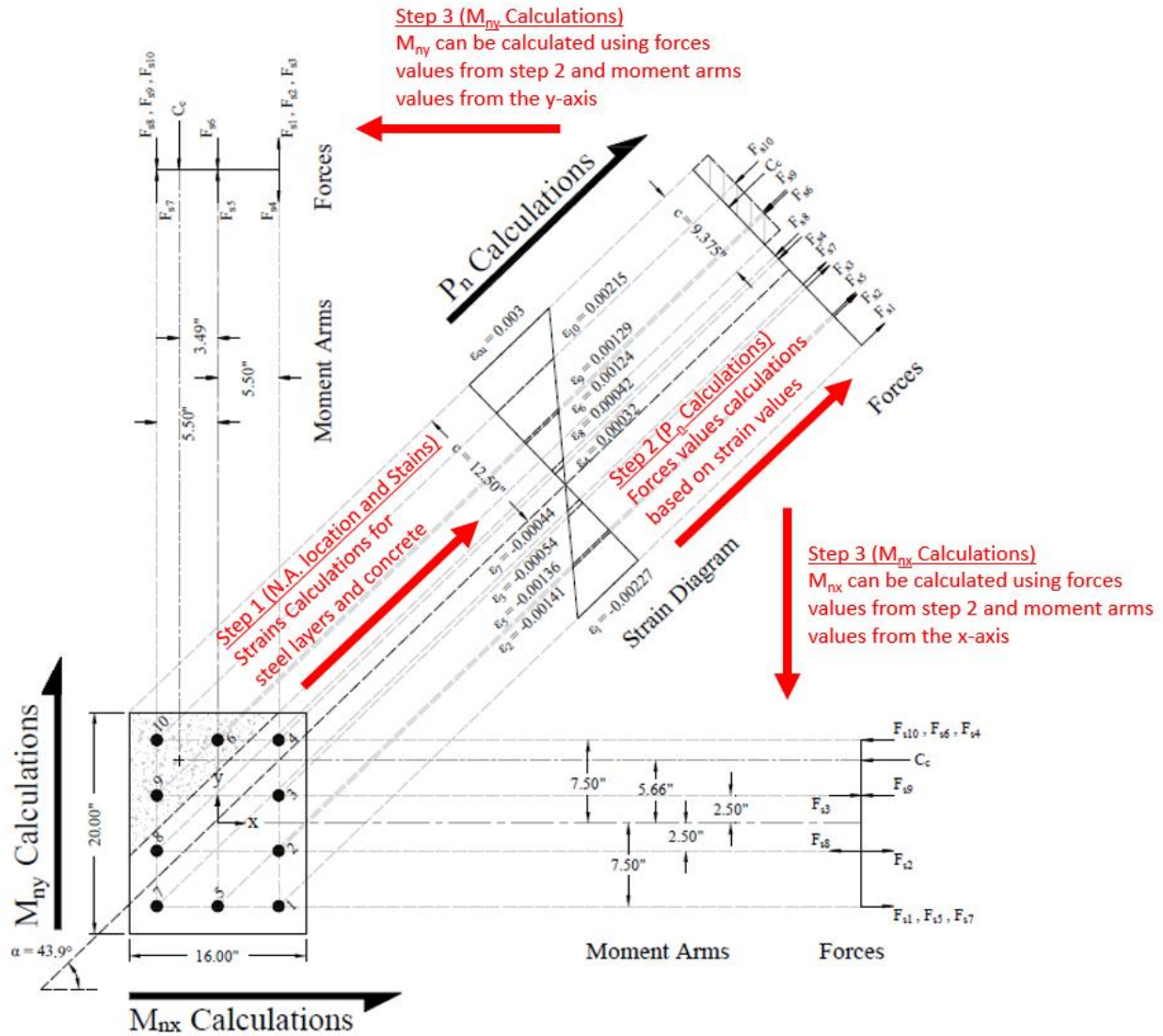


Figure 3 – Biaxial Flexural Strength Calculation Methods for a Reinforced Concrete Column.

1. Concrete Column Biaxial Strength Calculations

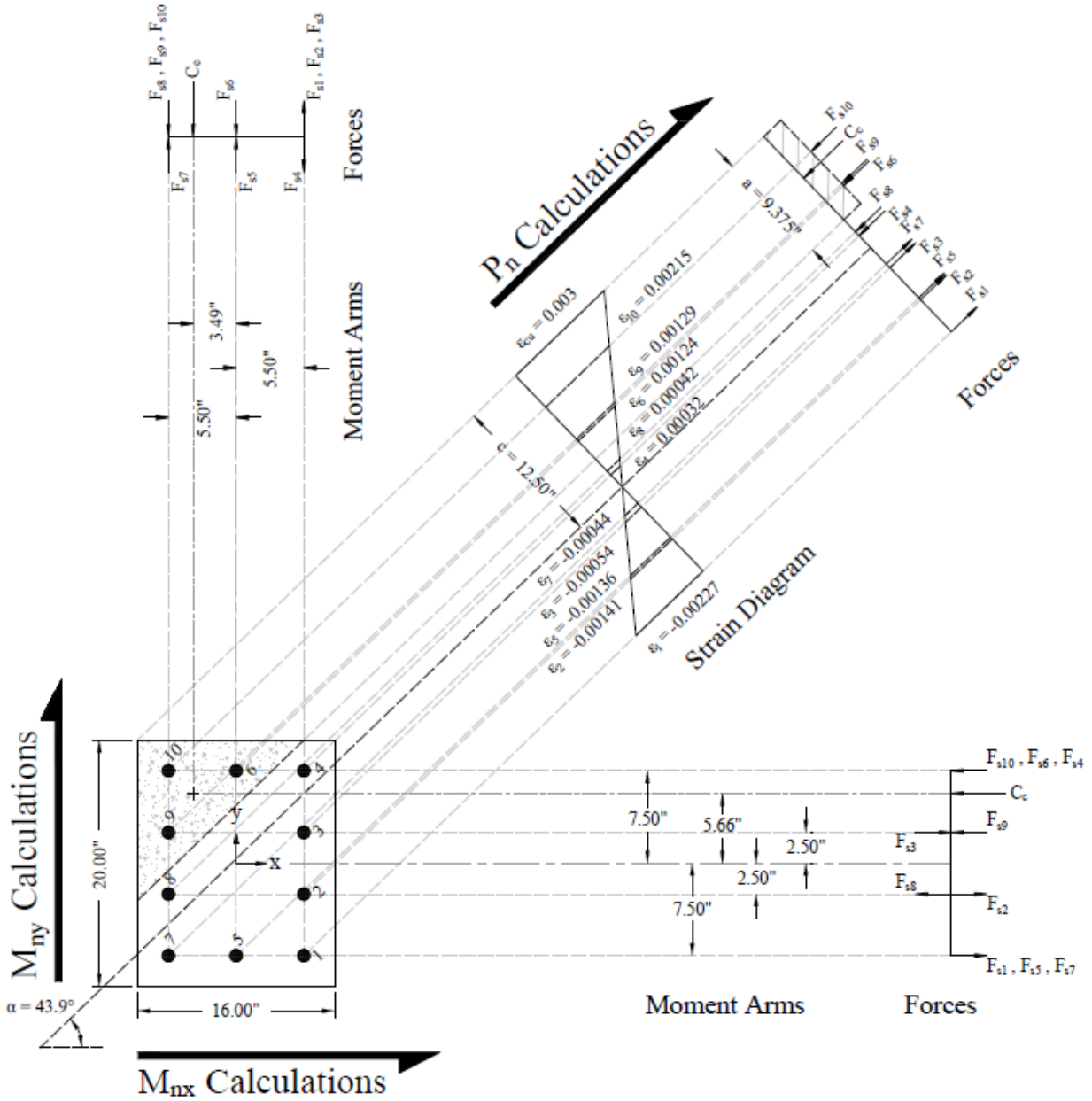


Figure 4 – Strains, Forces, and Moment Arms Diagram

1.1. Location of Neutral Axis and Concrete Compression Force

Use and iterative procedure to determine the nominal moment capacities for a point where the nominal axial load capacity, $P_n = 426$ kips and $M_{nx}/M_{ny} = 1.60$.

Several previous trials are conducted to determine the c value and the angle α . The following shows the last trial:

Try $c = 12.50$ in. and $\alpha = 43.9^\circ$, where c is the distance from the fiber of maximum compressive strain to the neutral axis and α is the angle of the neutral axis. ACI 318-19 (22.2.2.4.2)

$$\varepsilon_y = \frac{f_y}{E_s} = \frac{60}{29,000} = 0.00207$$

$$\varepsilon_{s1} = (c - d_1) \times \frac{\varepsilon_{cu}}{c} = (12.50 - 21.97) \times \frac{0.003}{12.50} = -0.00227 \text{ (Tension)} > \varepsilon_y \rightarrow \text{reinforcement has yielded}$$

$$\phi = 0.65 + 0.25 \times \left(\frac{\varepsilon_{s1} - \varepsilon_y}{0.003} \right) = 0.65 + 0.25 \times \left(\frac{0.00227 - 0.00207}{0.003} \right) = 0.667 \quad \text{ACI 318-19 (Table 21.2.2)}$$

$$a = \beta_1 \times c = 0.75 \times 12.50 = 9.375 \text{ in.} \quad \text{ACI 318-19 (22.2.2.4.1)}$$

$$\varepsilon_{cu} = 0.003 \quad \text{ACI 318-19 (22.2.2.1)}$$

Where:

a = Depth of equivalent rectangular stress block

$$\beta_1 = 0.85 - \frac{0.05 \times (f'_c - 4000)}{1000} = 0.85 - \frac{0.05 \times (6000 - 4000)}{1000} = 0.75 \quad \text{ACI 318-19 (Table 22.2.2.4.3)}$$

$$C_c = 0.85 \times f'_c \times A_{comp} = 0.85 \times 6000 \times 87.96 = 448.57 \text{ kip (Compression)} \quad \text{ACI 318-19 (22.2.2.4.1)}$$

Where:

$$A_{comp} = \frac{a^2}{2 \times \sin(\alpha) \times \cos(\alpha)} = \frac{(9.375)^2}{2 \times \sin(43.9^\circ) \times \cos(43.9^\circ)} = 87.96 \text{ in.}^2$$

$$\bar{x} = 3.49 \text{ in.} \quad \bar{y} = 5.66 \text{ in. (see the following figure)}$$

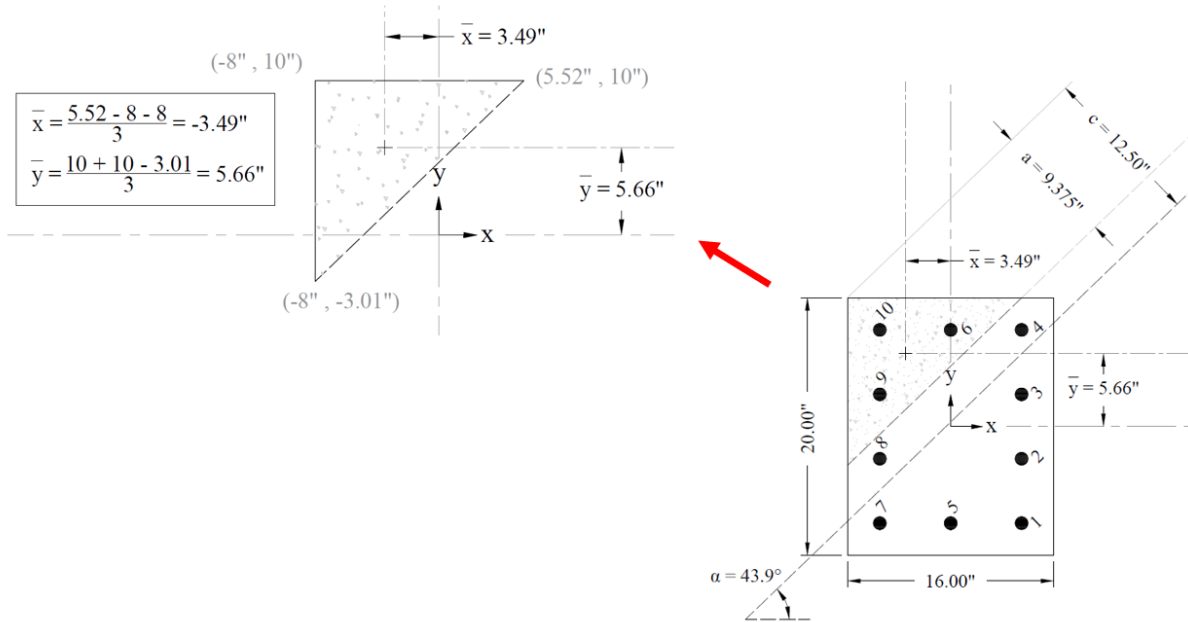


Figure 5 – Cracked Concrete Column Section Centroid Calculations

1.2. Strains and Forces Determination in Reinforcement Layers

For the 1st reinforcement layer:

$$\varepsilon_{s1} = -0.00227 \text{ (Tension)} > \varepsilon_y \rightarrow \text{reinforcement has yielded}$$

$$\therefore f_{s1} = f_y = -60000 \text{ psi}$$

$$F_{s1} = f_{s1} \times A_{s1} = -60000 \times (1 \times 0.79) = -47.4 \text{ kip (Tension)}$$

For the 9th reinforcement layer:

$$\varepsilon_{s9} = (c - d_9) \times \frac{\varepsilon_{cu}}{c} = (12.50 - 7.138) \times \frac{0.003}{12.50} = 0.00129 \text{ (Compression)} < \varepsilon_y \rightarrow \text{reinforcement has not yielded}$$

$$\therefore f_{s9} = \varepsilon_{s9} \times E_s = 0.00129 \times 29000000 = 37320 \text{ psi}$$

The area of the reinforcement in this layer is included in the area used to compute C_c ($a = 9.38$ in. $> d_9 = 7.14$ in.). As a result, it is necessary to subtract $0.85f'_c$ from f_{s9} before computing F_{s9} :

$$F_{s9} = f_{s9} \times A_{s9} = (37320 - 0.85 \times 6000) \times (1 \times 0.79) = 25.45 \text{ kip (Compression)}$$

The same procedure shown above can be repeated to calculate the forces in the remaining reinforcement layers, results are summarized in the following table:

Table 1 - Strains, internal force resultants and Moments

Layer	d, in.	ϵ , in./in.	f_s , psi	F_s , kip	C_c , kip	Moment arm (x), in.	M_y , kip-ft	Moment arm (y), in.	M_x , kip-ft
Concrete	---	0.00300	---	---	448.57	3.49	130.46	5.66	211.58
1	21.97	-0.00227	-60000	-47.40	---	-5.50	21.73	-7.50	29.63
2	18.37	-0.00141	-40841	-32.26	---	-5.50	14.79	-2.50	6.72
3	14.77	-0.00054	-15764	-12.45	---	-5.50	5.71	2.50	-2.59
4	11.16	0.00032	9312	7.36	---	-5.50	-3.37	7.50	4.60
5	18.16	-0.00136	-39373	-31.10	---	0.00	0.00	-7.50	19.44
6	7.35	0.00124	35851	24.29*	---	0.00	0.00	7.50	15.18
7	14.34	-0.00044	-12827	-10.13	---	5.50	-4.64	-7.50	6.33
8	10.74	0.00042	12250	9.68	---	5.50	4.44	-2.50	-2.02
9	7.14	0.00129	37320	25.45*	---	5.50	11.66	2.50	5.30
10	3.53	0.00215	60000	43.37*	---	5.50	19.88	7.50	27.11
Axial Force and Biaxial Bending Moments Capacities			P_n , kip	425.37		M_{ny} , kip-ft	200.64	M_{nx} , kip-ft	321.28
			ϕP_n , kip	283.72		ϕM_{ny} , kip-ft	133.83	ϕM_{nx} , kip-ft	214.29

* The area of the reinforcement in this layer has been included in the area used to compute C_c . As a result, $0.85f_c'$ is subtracted from f_s in the computation of F_s .

1.3. Calculation of P_n , M_{nx} and M_{ny}

$$P_n = C_c + \sum F_s \quad (+) = \text{Compression} \quad (-) = \text{Tension}$$

$$\phi P_n = \phi \times P_n = 0.667 \times P_n$$

$$M_{ny} = C_c \times \left(\frac{b}{2} - \bar{x}_c \right) + \sum_{i=1}^{n=10} \left(F_{si} \times \left(\frac{b}{2} - x_i \right) \right) \quad (+) = \text{Counter Clockwise} \quad (-) = \text{Clockwise}$$

$$\phi M_{ny} = \phi \times M_{ny} = 0.667 \times M_{ny}$$

$$M_{nx} = C_c \times \left(\frac{h}{2} - \bar{y}_c \right) + \sum_{i=1}^{n=10} \left(F_{si} \times \left(\frac{h}{2} - y_i \right) \right) \quad (+) = \text{Counter Clockwise} \quad (-) = \text{Clockwise}$$

$$\phi M_{nx} = \phi \times M_{nx} = 0.667 \times M_{nx}$$

Since the calculated P_n , and M_{nx}/M_{ny} are equal to the given P_n , and M_{nx}/M_{ny} ($P_n = 426$ kip and $M_{nx}/M_{ny} = 321/201 = 1.60$), the assumptions that $c = 12.5$ in. and $\alpha = 43.9^\circ$ are verified as correct.

2. Column Biaxial Bending Interaction Diagram – spColumn Software

[spColumn](#) is a StructurePoint software program that performs the analysis and design of reinforced concrete sections subjected to axial force combined with uniaxial or biaxial bending. Using the provisions of the Strength Design Method and Unified Design Provisions, slenderness considerations are used for moment magnification due to second order effect (P-Delta) for sway and non-sway frames.

For biaxial runs, the values of maximum compressive axial load capacity and maximum tensile load capacity are computed. These two values set the range within which the moment capacities are computed for a predetermined number of axial load values. For each level of axial load, the section is rotated in 10-degree increments from 0 degrees to 360 degrees and the M_x and M_y moment capacities are computed. Thus, for each level of axial load, an M_x - M_y contour is developed. Repeating this for the entire range of axial loads, the three-dimensional failure surface is computed. A three-dimensional visualization of the resulting entire nominal and factored failure surface is provided to support enhanced understanding of the section capacity.

The “**biaxial**” feature allows the user to investigate the P-M interaction diagrams, the M_x - M_y moment contour plots, as well as the 3D failure surface for even the most irregular column and shear wall sections quickly, simply, and accurately.

For this column section, we ran in investigation mode with “**biaxial**” option for “Run Axis” using the ACI 318-19.

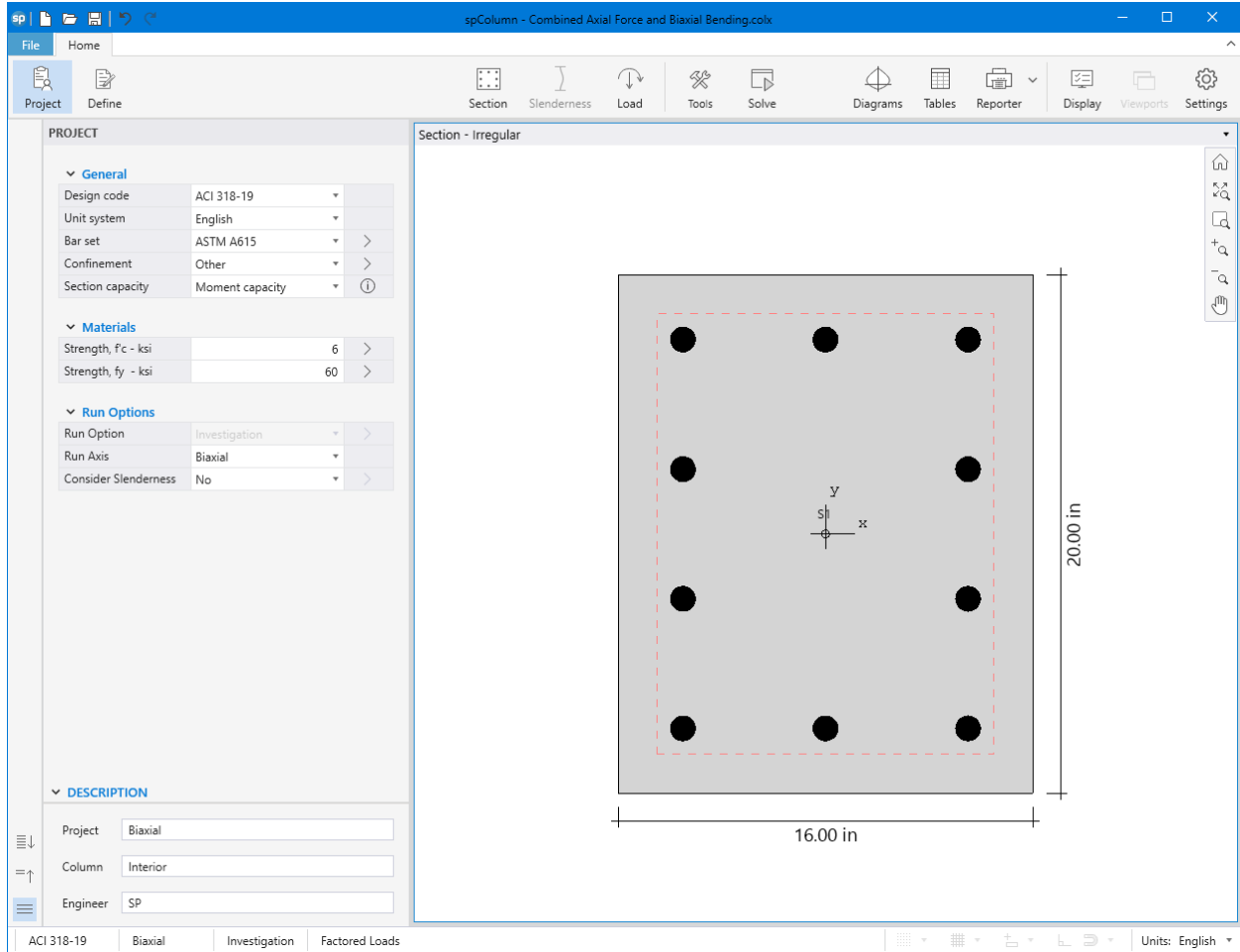


Figure 6 – spColumn Interface

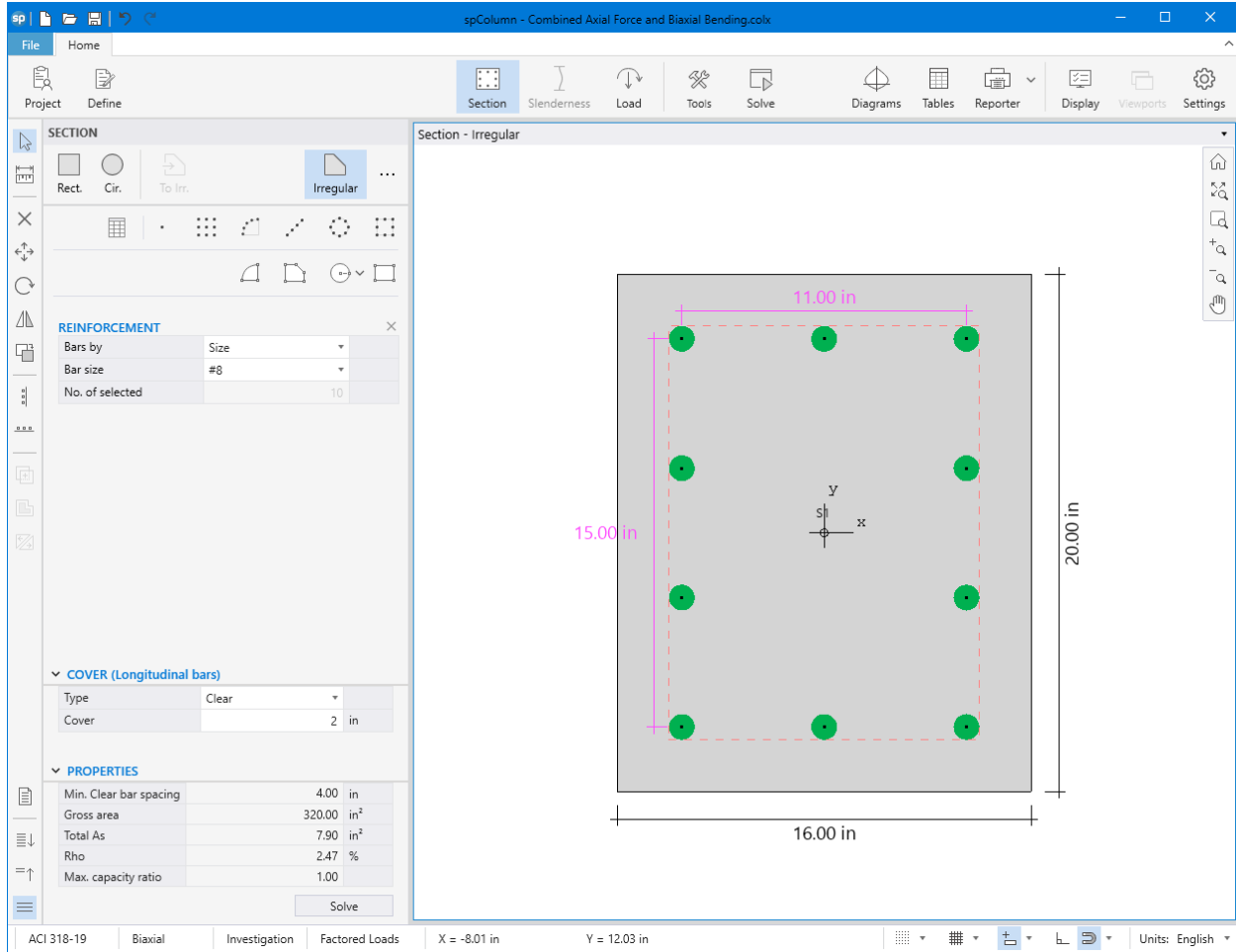


Figure 7 – spColumn Model Editor

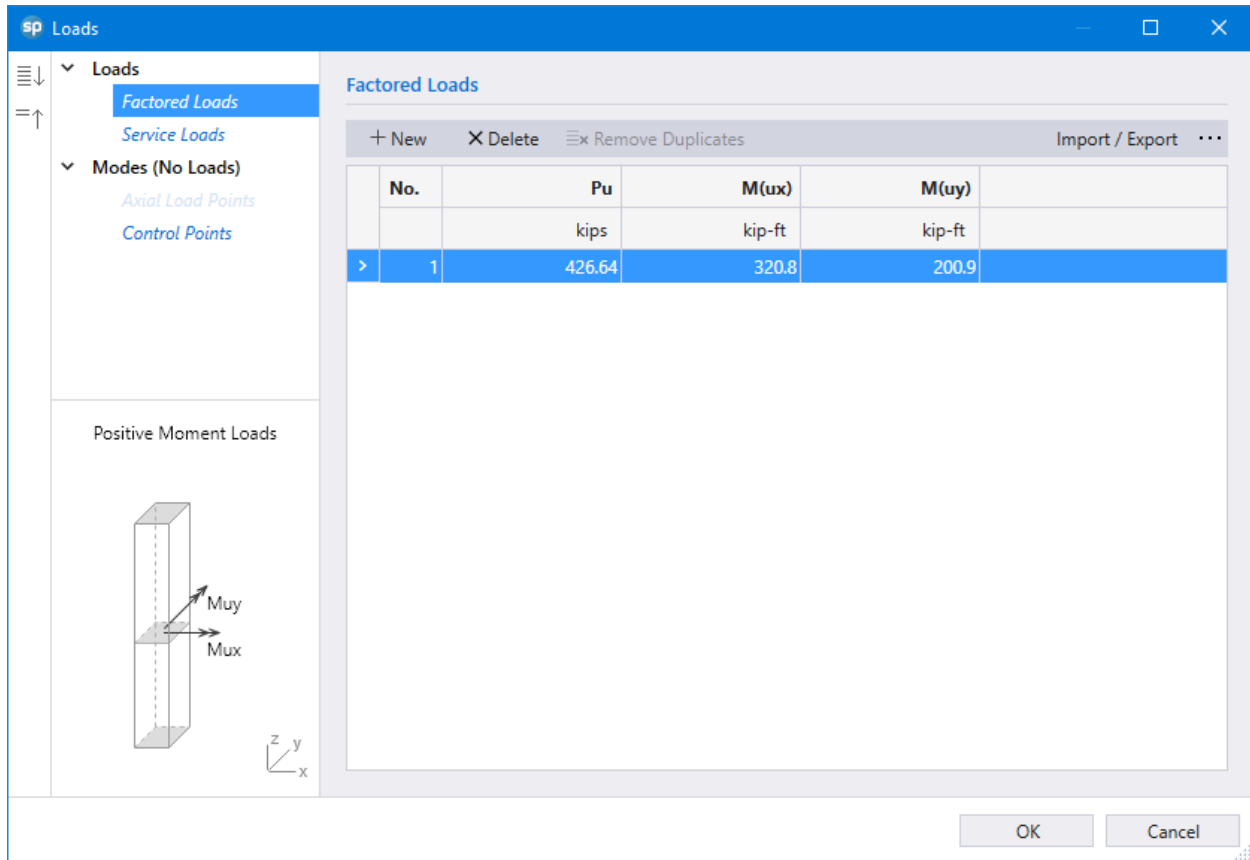


Figure 8 – Defining Loads / Modes (spColumn)

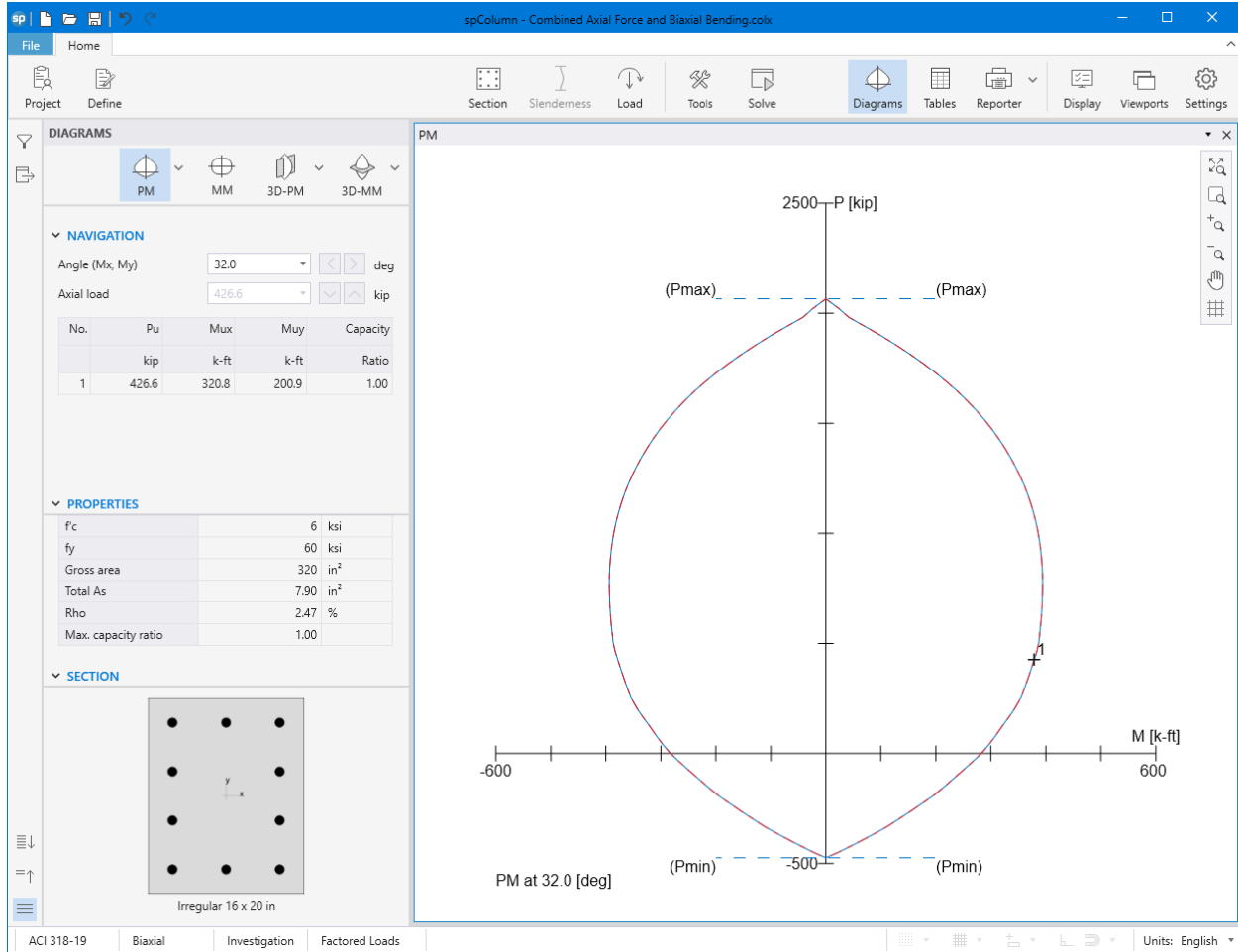
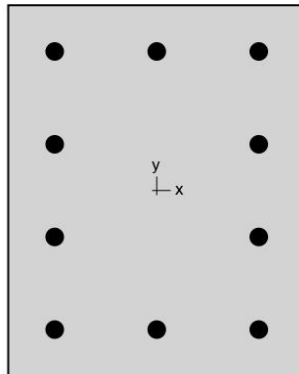


Figure 9 – Column Section Interaction Diagram at 32° (spColumn)



spColumn v10.00 (TM)
Computer program for the Strength Design of Reinforced Concrete Sections
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1. General Information

File Name	... \Combined Axial Force and Biaxial Bending.colx
Project	Biaxial
Column	Interior
Engineer	SP
Code	ACI 318-19
Bar Set	ASTM A615
Units	English
Run Option	Investigation
Run Axis	Biaxial
Slenderness	Not Considered
Column Type	Structural
Capacity Method	Moment capacity

2. Material Properties

2.1. Concrete

Type	Standard
f'_c	6 ksi
E_c	4415.21 ksi
f_t	5.1 ksi
ϵ_u	0.003 in/in
β_1	0.75

2.2. Steel

Type	Standard
f_y	60 ksi
E_s	29000 ksi
ϵ_{sy}	0.00206897 in/in

3. Section

3.1. Shape and Properties

Type	Irregular
A_g	320 in ²
I_x	10666.7 in ⁴
I_y	6826.67 in ⁴
r_x	5.7735 in
r_y	4.6188 in
X_o	0 in
Y_o	0 in

3.2. Section Figure

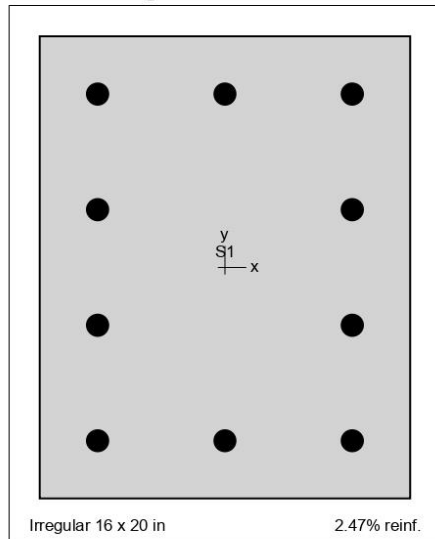


Figure 1: Column section

3.3. Solids

3.3.1. S1

Points	X in	Y in	Points	X in	Y in	Points	X in	Y in
1	-8.0	-10.0	2	8.0	-10.0	3	8.0	10.0
4	-8.0	10.0						

4. Reinforcement

4.1. Bar Set: ASTM A615

Bar	Diameter in	Area in ²	Bar	Diameter in	Area in ²	Bar	Diameter in	Area in ²
#3	0.38	0.11	#4	0.50	0.20	#5	0.63	0.31
#6	0.75	0.44	#7	0.88	0.60	#8	1.00	0.79
#9	1.13	1.00	#10	1.27	1.27	#11	1.41	1.56
#14	1.69	2.25	#18	2.26	4.00			

4.2. Confinement and Factors

Confinement type	Other
For #10 bars or less	#3 ties
For larger bars	#4 ties
Capacity Reduction Factors	
Axial compression, (a)	1
Tension controlled ϕ , (b)	1
Compression controlled ϕ , (c)	1

Capacity reduction factors set to 1.0 in spColumn input for illustration purposes

4.3. Arrangement

Pattern	Irregular
Bar layout	---
Cover to	---
Clear cover	---
Bars	---
Total steel area, A_s	7.90 in ²
Rho	2.47 %
Minimum clear spacing	4.00 in

4.4. Bars Provided

Area in ²	X in	Y in	Area in ²	X in	Y in	Area in ²	X in	Y in
0.79	-5.5	-7.5	0.79	0.0	-7.5	0.79	5.5	-7.5
0.79	5.5	-2.5	0.79	5.5	2.5	0.79	5.5	7.5
0.79	0.0	7.5	0.79	-5.5	7.5	0.79	-5.5	2.5
0.79	-5.5	-2.5						

5. Control Points

About Point	P kip	X-Moment k-ft	Y-Moment k-ft	NA Depth in	d_t Depth in	ϵ_t	ϕ
X @ Max compression	2065.7	0.00	0.00	56.39	17.50	-0.00207	1.00000
X @ Allowable comp.	2065.7	0.00	0.00	56.39	17.50	-0.00207	1.00000
X @ $f_s = 0.0$	1302.8	396.30	0.00	17.50	17.50	0.00000	1.00000
X @ $f_s = 0.5 f_y$	911.0	474.89	0.00	13.01	17.50	0.00103	1.00000
X @ Balanced point	623.2	505.40	0.00	10.36	17.50	0.00207	1.00000
X @ Tension control	255.1	426.91	0.00	6.51	17.50	0.00507	1.00000
X @ Pure bending	0.0	315.93	0.00	4.24	17.50	0.00939	1.00000
X @ Max tension	-474.0	0.00	0.00	0.00	17.50	9.99999	1.00000
Y @ Max compression	2065.7	0.00	0.00	43.50	13.50	-0.00207	1.00000
Y @ Allowable comp.	2065.7	0.00	0.00	43.50	13.50	-0.00207	1.00000
Y @ $f_s = 0.0$	1254.2	0.00	332.32	13.50	13.50	0.00000	1.00000
Y @ $f_s = 0.5 f_y$	874.5	0.00	394.02	10.04	13.50	0.00103	1.00000
Y @ Balanced point	594.2	0.00	420.96	7.99	13.50	0.00207	1.00000
Y @ Tension control	234.6	0.00	338.51	5.02	13.50	0.00507	1.00000
Y @ Pure bending	0.0	0.00	243.63	3.06	13.50	0.01024	1.00000
Y @ Max tension	-474.0	0.00	0.00	0.00	13.50	9.99999	1.00000
-X @ Max compression	2065.7	0.00	0.00	56.39	17.50	-0.00207	1.00000
-X @ Allowable comp.	2065.7	0.00	0.00	56.39	17.50	-0.00207	1.00000
-X @ $f_s = 0.0$	1302.8	-396.30	0.00	17.50	17.50	0.00000	1.00000
-X @ $f_s = 0.5 f_y$	911.0	-474.89	0.00	13.01	17.50	0.00103	1.00000
-X @ Balanced point	623.2	-505.40	0.00	10.36	17.50	0.00207	1.00000
-X @ Tension control	255.1	-426.91	0.00	6.51	17.50	0.00507	1.00000
-X @ Pure bending	0.0	-315.93	0.00	4.24	17.50	0.00939	1.00000
-X @ Max tension	-474.0	0.00	0.00	0.00	17.50	9.99999	1.00000
-Y @ Max compression	2065.7	0.00	0.00	43.50	13.50	-0.00207	1.00000
-Y @ Allowable comp.	2065.7	0.00	0.00	43.50	13.50	-0.00207	1.00000
-Y @ $f_s = 0.0$	1254.2	0.00	-332.32	13.50	13.50	0.00000	1.00000
-Y @ $f_s = 0.5 f_y$	874.5	0.00	-394.02	10.04	13.50	0.00103	1.00000
-Y @ Balanced point	594.2	0.00	-420.96	7.99	13.50	0.00207	1.00000
-Y @ Tension control	234.6	0.00	-338.51	5.02	13.50	0.00507	1.00000
-Y @ Pure bending	0.0	0.00	-243.63	3.06	13.50	0.01024	1.00000
-Y @ Max tension	-474.0	0.00	0.00	0.00	13.50	9.99999	1.00000

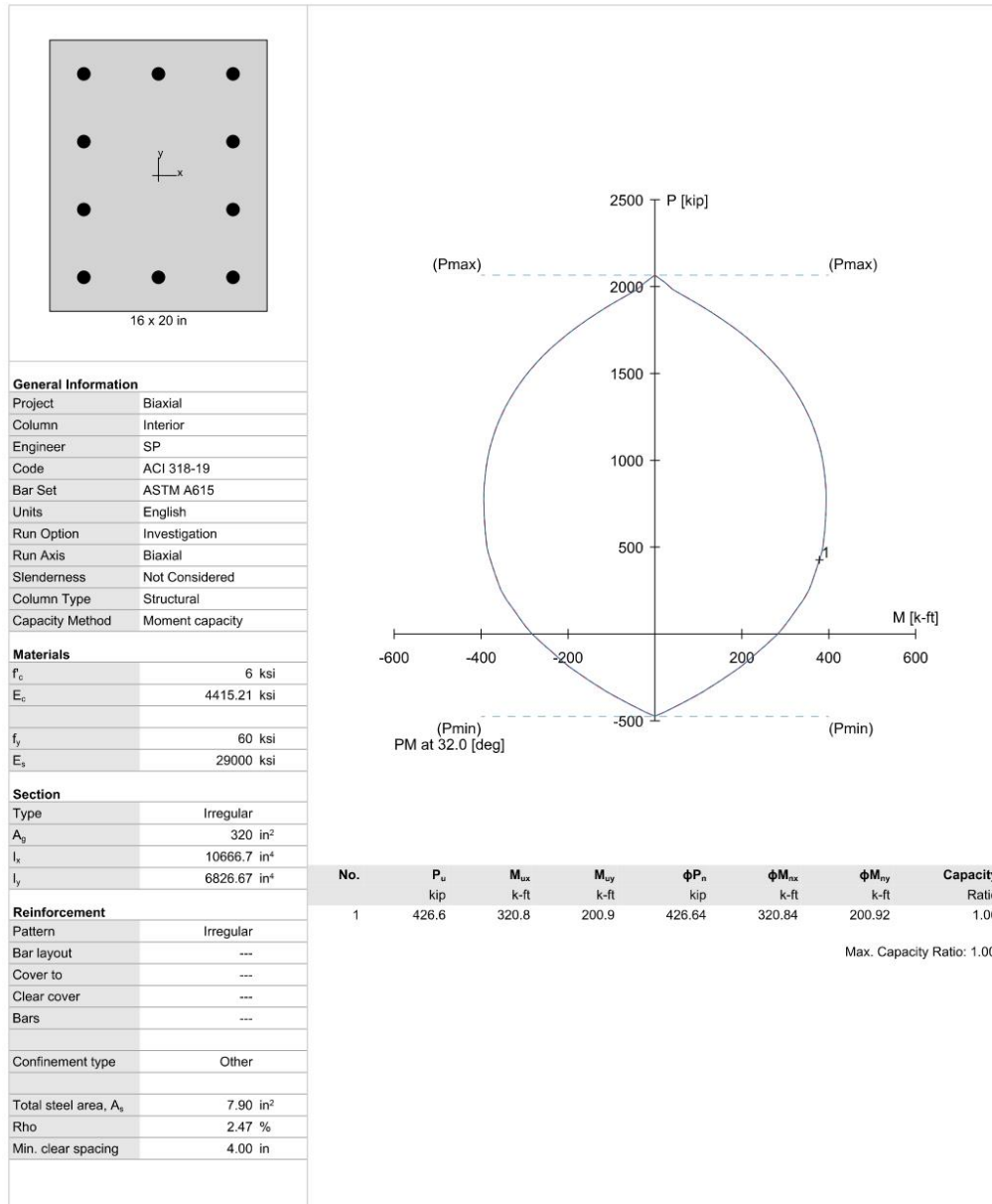
6. Factored Loads and Moments with Corresponding Capacity Ratios

NOTE: Calculations are based on "Moment Capacity" Method.

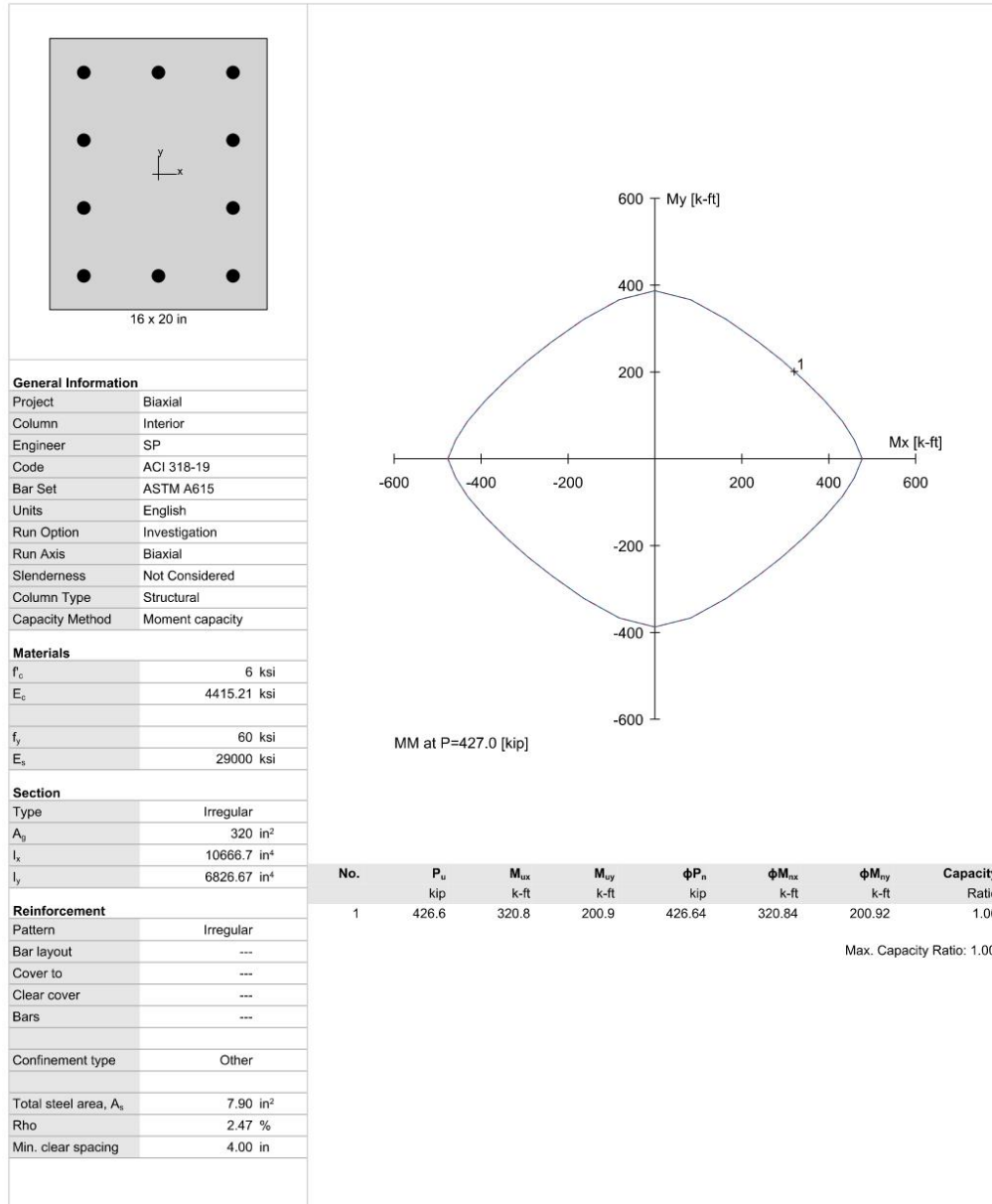
No.	Demand			Capacity			Parameters at Capacity			Capacity Ratio
	P_u kip	M_{ux} k-ft	M_{uy} k-ft	ϕP_n kip	ϕM_{nx} k-ft	ϕM_{ny} k-ft	NA Depth in	ϵ_t	ϕ	
1	426.64	320.80	200.90	426.64	320.84	200.92	12.44	0.00228	1.000	1.00

7. Diagrams

7.1. PM at $\theta=32$ [deg]



7.2. MM at P=427 [kip]



General Information	
Project	Biaxial
Column	Interior
Engineer	SP
Code	ACI 318-19
Bar Set	ASTM A615
Units	English
Run Option	Investigation
Run Axis	Biaxial
Slenderness	Not Considered
Column Type	Structural
Capacity Method	Moment capacity
Materials	
f'_c	6 ksi
E_c	4415.21 ksi
f_y	60 ksi
E_s	29000 ksi
Section	
Type	Irregular
A_g	320 in ²
I_x	10666.7 in ⁴
I_y	6826.67 in ⁴
Reinforcement	
Pattern	Irregular
Bar layout	---
Cover to	---
Clear cover	---
Bars	---
Confinement type	Other
Total steel area, A_s	7.90 in ²
Rho	2.47 %
Min. clear spacing	4.00 in

3. Summary and Comparison of Design Results

Table 2 - Comparison of Results			
Parameter	Reference	Hand	spColumn
c, in.	12.50	12.50	12.44
d ₁ , in.	21.97	21.97	21.97
ε _{s1} , in./in.	0.00227	0.00227	0.00228
P _n , kip	426.0	425.37	426.64
M _{nx} , kip-ft	321.0	321.28	320.84
M _{ny} , kip-ft	201.0	200.64	200.92

In all of the hand calculations and the reference used illustrated above, the results are in good agreement with the automated exact results obtained from the [spColumn](#) program.

4. Conclusions & Observations

The analysis of the reinforced concrete section performed by [spColumn](#) conforms to the provisions of the Strength Design Method and Unified Design Provisions with all conditions of strength satisfying the applicable conditions of equilibrium and strain compatibility.

In most building design calculations, such as the examples shown for [flat plate](#) or [flat slab](#) concrete floor systems, all building columns may be subjected to biaxial bending (M_x and M_y) due to lateral effects and unbalanced moments from both directions of analysis. This requires an investigation of the column P- M_x - M_y interaction diagram in two directions simultaneously (axial force interaction with biaxial bending).

This example shows the calculations needed to obtain one point on the three-dimensional failure surface (biaxial M_x - M_y interaction diagram). Generating the three-dimensional failure surface (interaction diagram) for a column section subjected to a combined axial force and biaxial bending moments is tedious and challenging for engineers and the use of a computer aid can save time and eliminate errors. StructurePoint's [spColumn](#) program can, quickly, simply and accurately generate the three-dimensional failure surface (interaction diagram) for all commonly encountered column, beam or wall sections in addition to highly complex and irregular cross-sections.

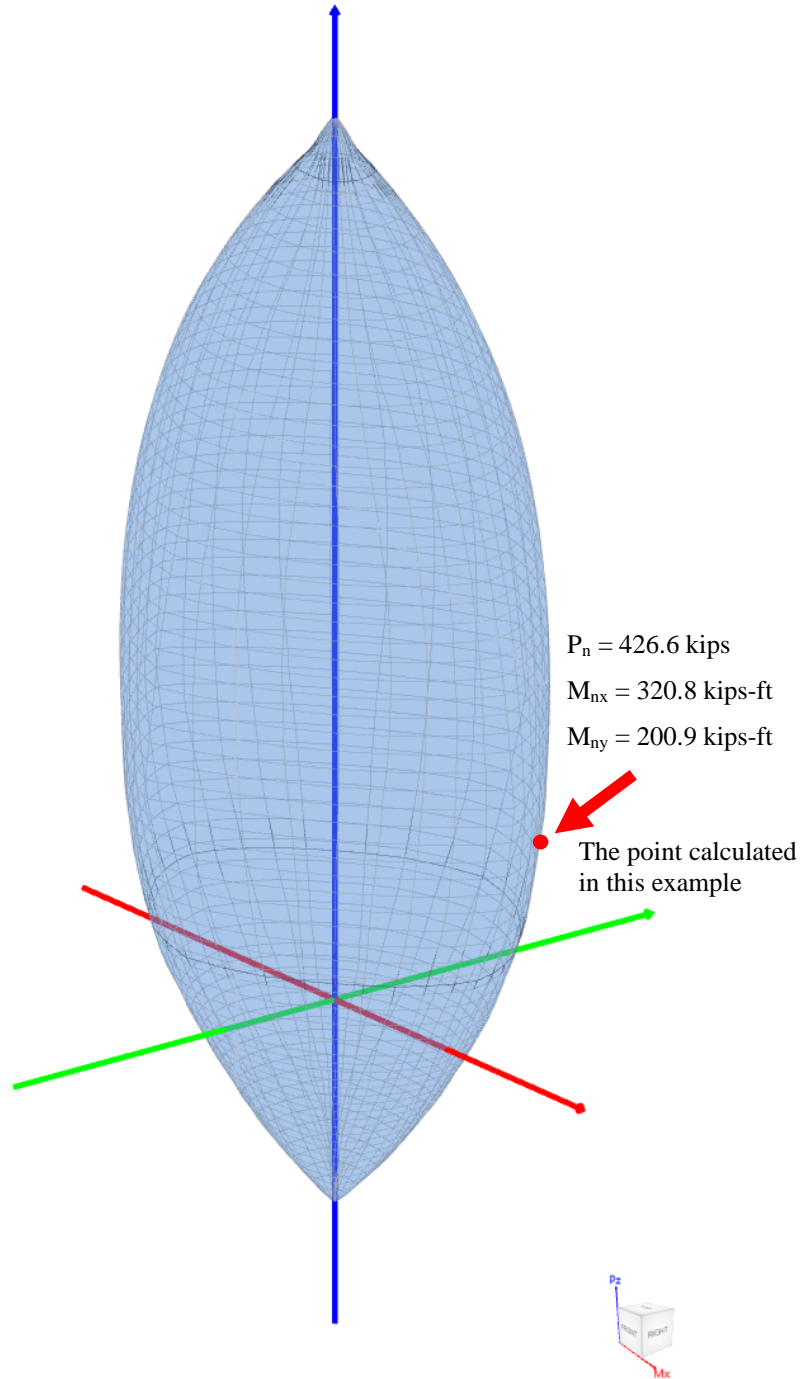


Figure 10 – Nominal Interaction Diagram in Two Directions (Biaxial) (spColumn)

The [spColumn](#) “Diagrams” module is a very powerful tool especially for investigating interaction diagrams (failure surfaces) for columns and walls sections subjected to a combined axial force and biaxial bending moments. The module allows the user to view and analyze 2D interaction diagrams and contours along with 3D failure surfaces in a multi viewport environment. The following figure shows three views of:

1. P-M interaction diagram cut at angle of 32°
2. Mx-My interaction diagram cut at axial load of 426.6 kip in compression
3. A 3D failure surface (interaction diagram) showing the point calculated in this example.

Figures 12 and 13 show 3D visualization of failure surface with a horizontal and vertical plane cut, respectively.

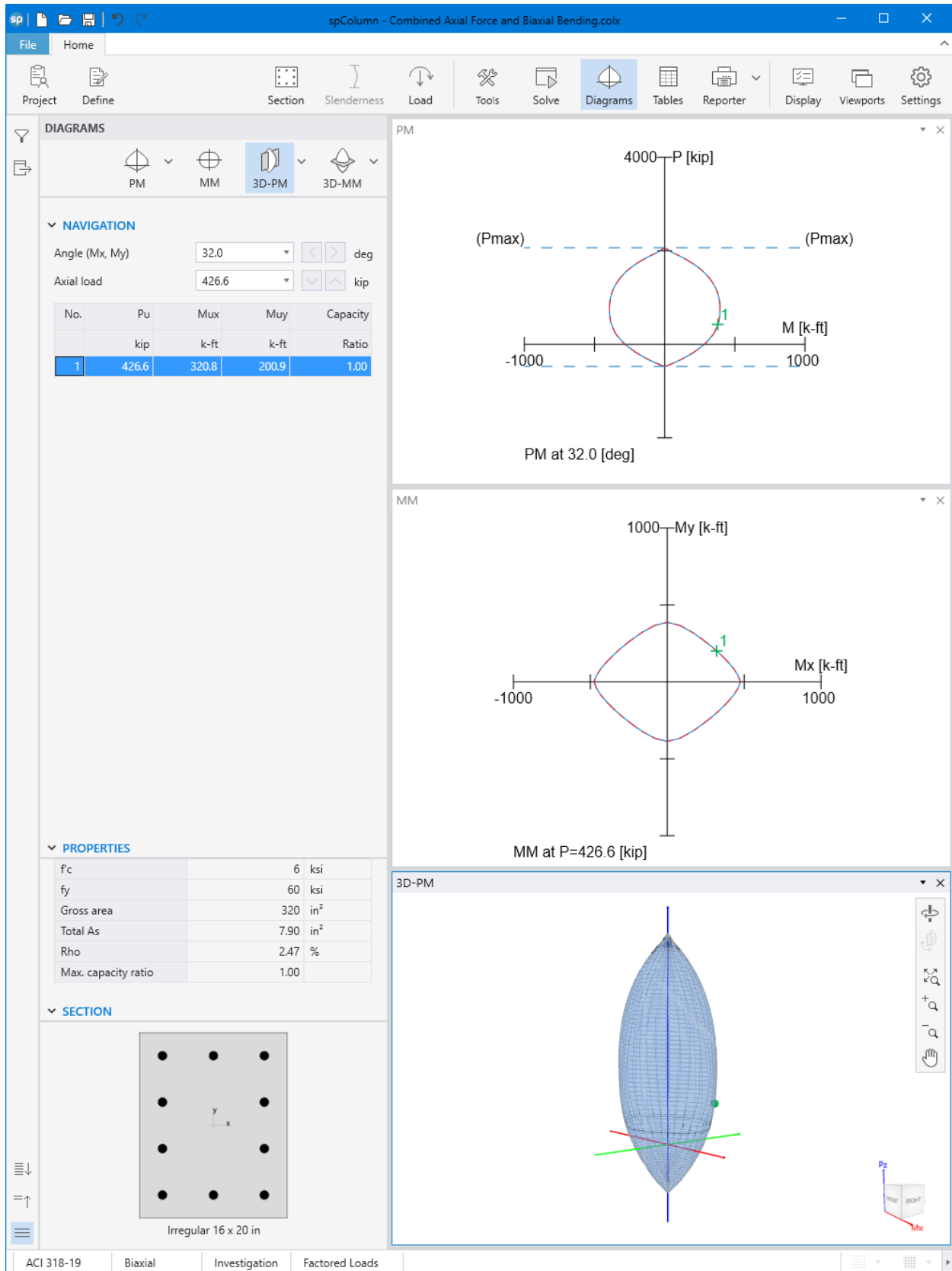


Figure 11 – Diagrams Module (spColumn)

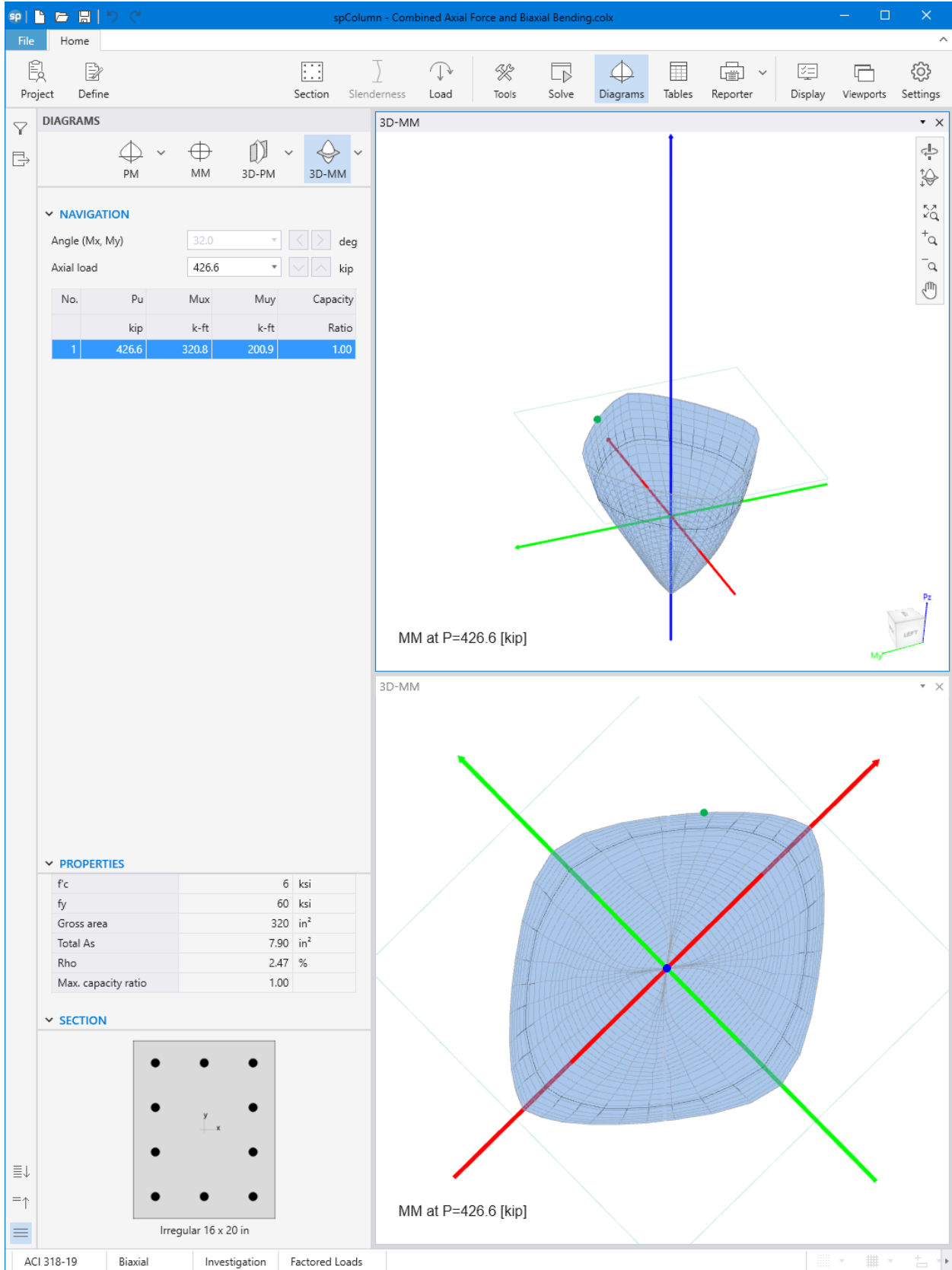


Figure 12 – 3D Visualization of Failure Surface with a Horizontal Plane Cut at $P = 426.6$ kip (spColumn)

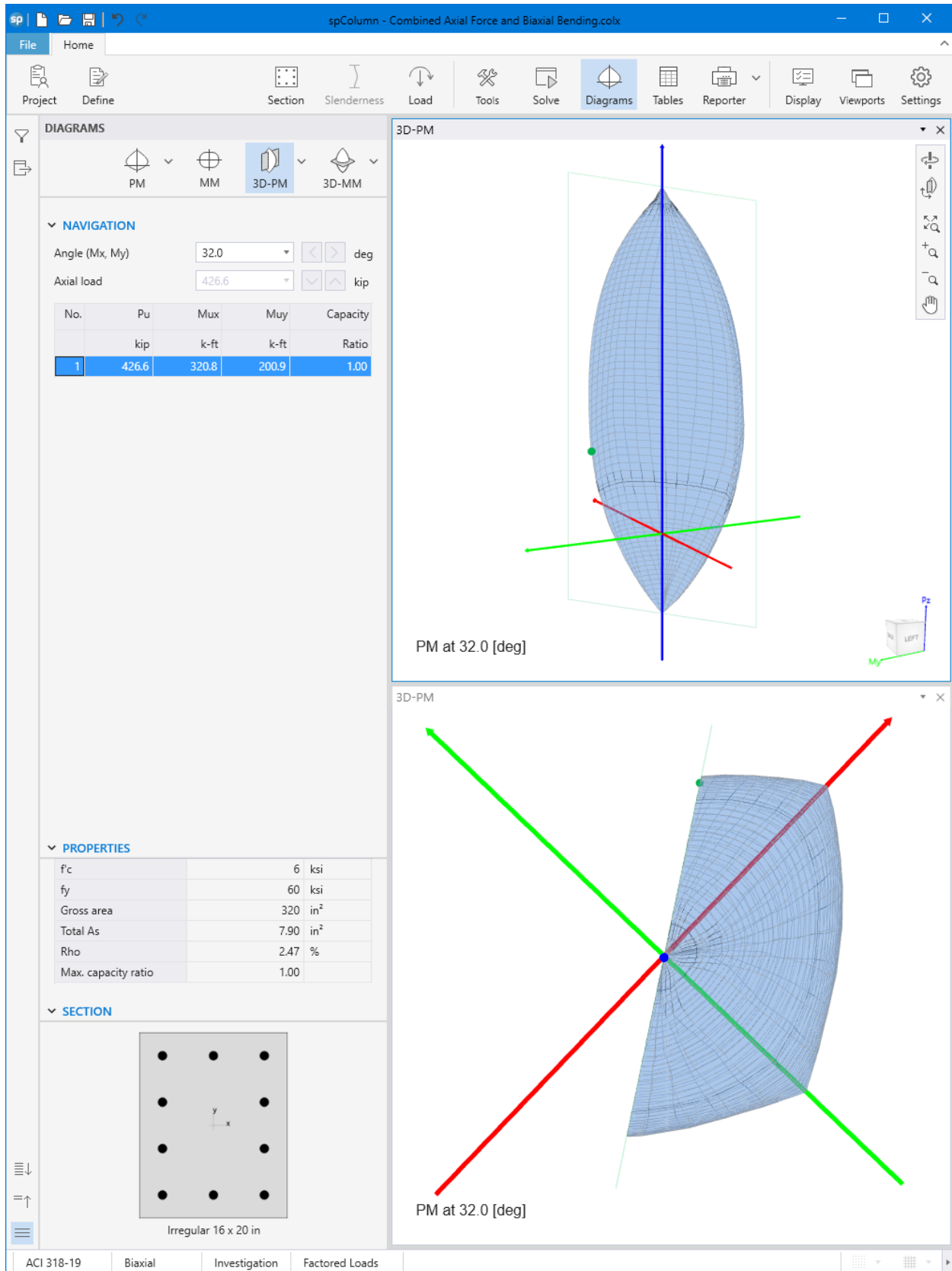


Figure 13 – 3D Visualization of Failure Surface with a Vertical Plane Cut at 32° (spColumn)