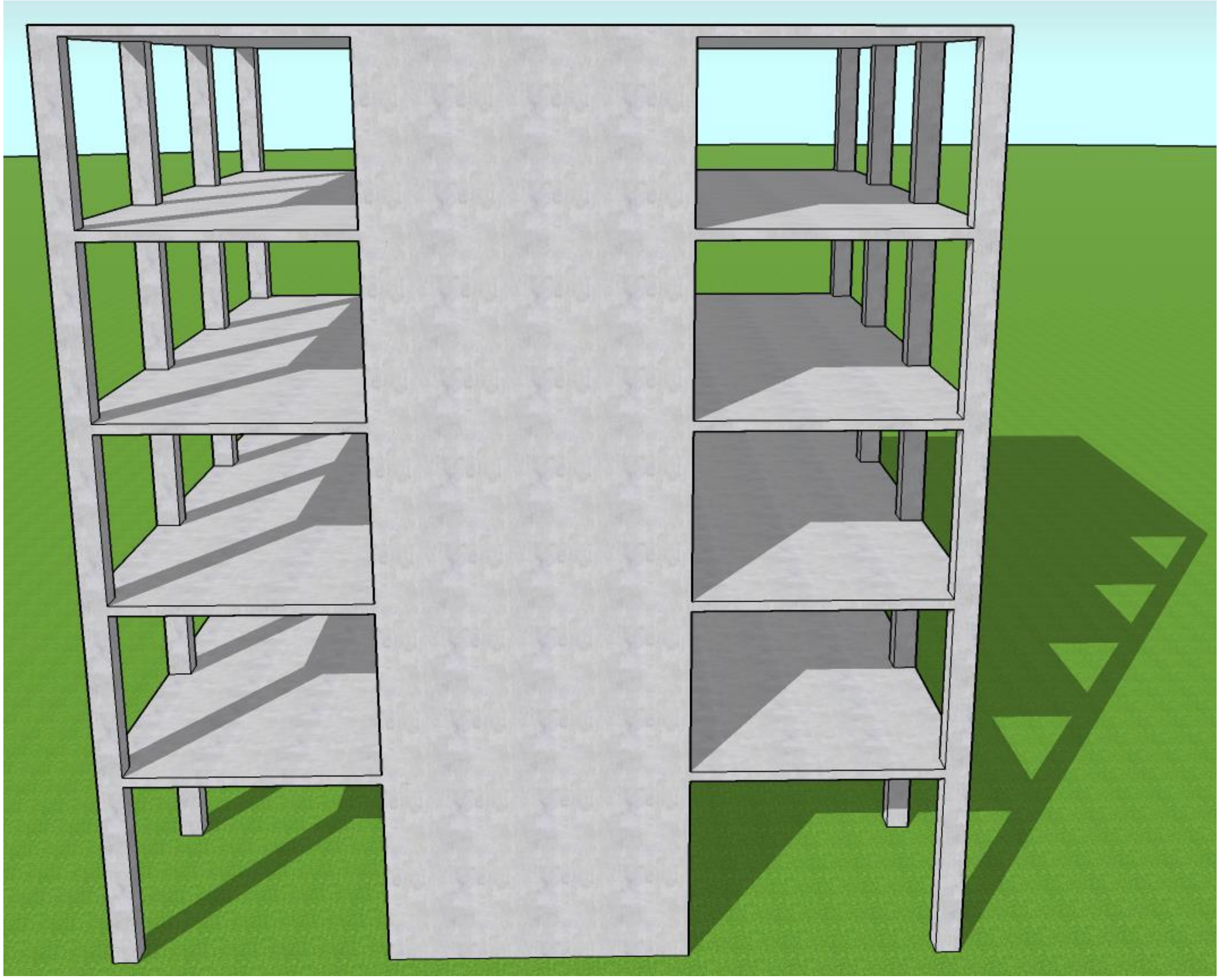
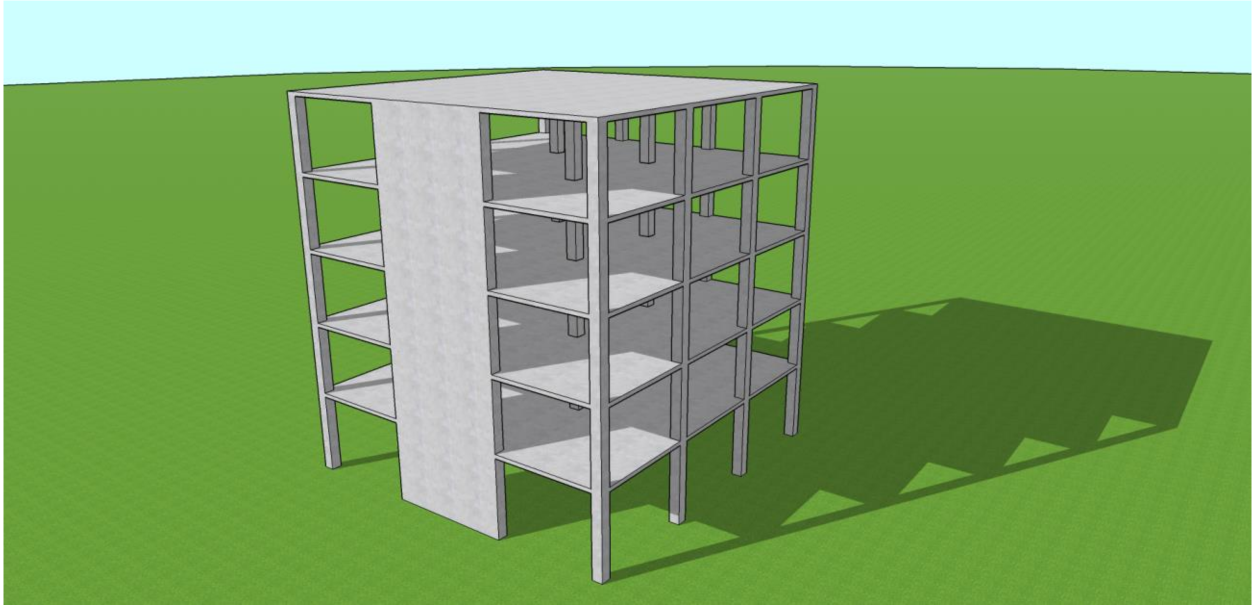
Reinforced Concrete Shear Wall Analysis and Design





Reinforced Concrete Shear Wall Analysis and Design

A structural reinforced concrete shear wall in a 5-story building provides lateral and gravity load resistance for the applied load as shown in the figure below. Shear wall section and assumed reinforcement is investigated after analysis to verify suitability for the applied loads.

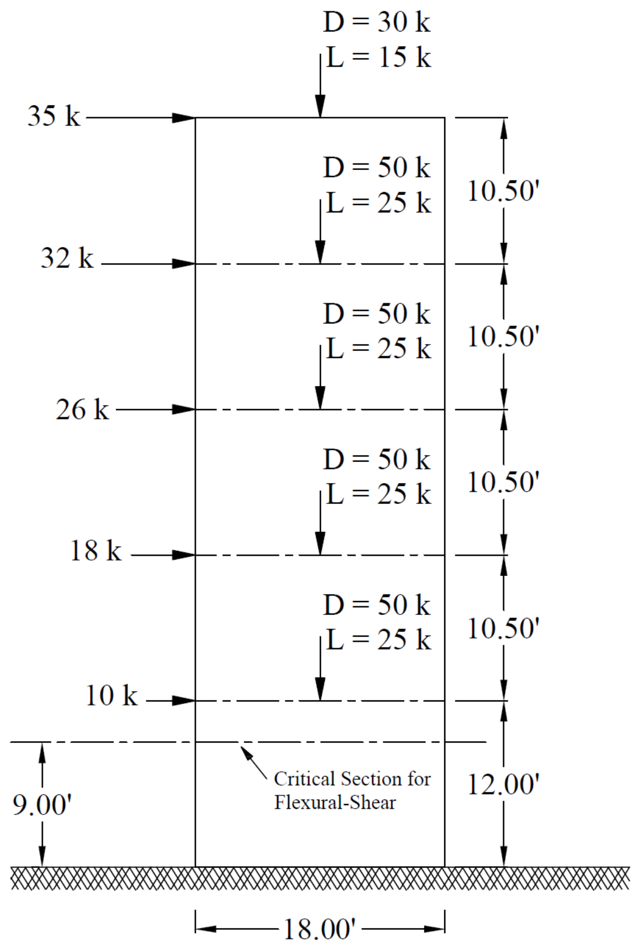


Figure 1 – Reinforced Concrete Shear Wall Geometry and Loading

Contents

Code

Building Code Requirements for Structural Concrete (ACI 318-14) and Commentary (ACI 318R-14)

Reference

Reinforced Concrete Mechanics and Design, 7th Edition, 2016, James Wight, Pearson, Example 18-2

Design Data

f_c' = 4,000 psi normal weight concrete

f_y = 60,000 psi

Slab thickness = 7 in.

Wall thickness = 10 in.

Wall length = 18 ft

Vertical reinforcement: #5 bars at 18 in. on centers in each face ($A_{s,\ vertical}$ = #5 @ 18 in.)

Horizontal reinforcement: #4 bars at 16 in. on centers in each face ($A_{s,\ horizontal}$ = #4 @ 16 in.)

1. Minimum Reinforcement Requirements (Reinforcement Percentage and Spacing)

1.1. Horizontal Reinforcement Check

$$\rho_t = \frac{A_{v,horizontal}}{h \times s_2} = \frac{2 \times 0.2}{10 \times 16} = 0.0025$$ ***ACI 318-14 (2.2)***

$$\rho_t = 0.0025 \geq \rho_{t,\min} = 0.0025 \text{ (o.k)}$$ ***ACI 318-14 (11.6.2(b))***

$$s_{t,\max} = \text{smallest of} \begin{Bmatrix} 3 \times h \\ 18 \text{ in.} \\ l_w / 5 \end{Bmatrix} = \text{smallest of} \begin{Bmatrix} 3 \times 10 \\ 18 \text{ in.} \\ 18/5 \end{Bmatrix} = \text{smallest of} \begin{Bmatrix} 30 \text{ in.} \\ 18 \text{ in.} \\ 43.2 \text{ in.} \end{Bmatrix} = 18 \text{ in.}$$ ***ACI 318-14 (11.7.3.1)***

$$s_{t,provided} = 16 \text{ in.} < s_{t,\max} = 18 \text{ in. (o.k)}$$

1.2. Vertical Reinforcement Check

$$\rho_l = \frac{A_{v,vertical}}{h \times s_1} = \frac{2 \times 0.31}{10 \times 18} = 0.00344$$ ***ACI 318-14 (2.2)***

$$\rho_{l,\min} = \text{greater of} \begin{Bmatrix} 0.0025 + 0.5\left(2.5 - \frac{h_w}{l_w}\right)(\rho_t - 0.0025) \\ 0.0025 \end{Bmatrix}$$ ***ACI 318-14 (11.6.2(a))***

$$\rho_{l,\min} = \text{greater of} \begin{Bmatrix} 0.0025 + 0.5\left(2.5 - \frac{h_w}{l_w}\right)(0.0025 - 0.0025) \\ 0.0025 \end{Bmatrix} = \text{greater of} \begin{Bmatrix} 0.0025 \\ 0.0025 \end{Bmatrix} = 0.0025$$

$$\rho_l = 0.00344 \geq \rho_{l,\min} = 0.0025 \text{ (o.k)}$$ ***ACI 318-14 (11.6.2(a))***

$$s_{l,\max} = \text{smallest of} \begin{Bmatrix} 3 \times h \\ 18 \text{ in.} \\ l_w / 3 \end{Bmatrix} = \text{smallest of} \begin{Bmatrix} 3 \times 10 \\ 18 \text{ in.} \\ 18/3 \end{Bmatrix} = \text{smallest of} \begin{Bmatrix} 30 \text{ in.} \\ 18 \text{ in.} \\ 72 \text{ in.} \end{Bmatrix} = 18 \text{ in.}$$ ***ACI 318-14 (11.7.2.1)***

$$s_{l,provided} = 18 \text{ in.} \leq s_{l,\max} = 18 \text{ in. (o.k)}$$

2. Neutral Axis Depth Determination

$$M_{base} = 35\times54+32\times43.5+26\times33+18\times22.5+10\times12 = 4,670 \text{ kip-ft}$$

The load factor for strength-level wind force = 1.0

$$M_{u,base} = 1.0\times4,670 = 4,670 \text{ kip-ft}$$

$$N_u = 0.9\times N_D = 0.9\times(30+50+50+50+50) = 207 \text{ kips}$$ ***ACI 318-14 (Eq.5.3.1f)***

$$\beta_1 = 0.85-\frac{0.05\times\left(f_c^{'}-4000\right)}{1000} = 0.85-\frac{0.05\times(4000-4000)}{1000} = 0.85$$ ***ACI 318-14 (Table 22.2.2.4.3)***

$$\omega = \rho_l \frac{f_y}{f_c^{'}} = 0.00344\times\frac{60}{4} = 0.0516$$

$$\alpha = \frac{N_u}{h\times l_w\times f_c^{'}} = \frac{207}{10\times216\times4} = 0.0240$$

$$c = \left(\frac{\alpha+\omega}{0.85\beta_1+2\omega}\right)l_w = \left(\frac{0.0240+0.0516}{0.85\times0.85+2\times0.0516}\right)\times216 = 19.8 \text{ in.}$$

Assume the effective flexural depth (d) is approximately equal to $0.8l_w$ = 173 in. ***ACI 318-14 (11.5.4.2)***

$$c = 19.8 \text{ in.} << d = 173 \text{ in.} \rightarrow \text{Tension controlled section}$$

$$\therefore \phi = 0.90$$ ***ACI 318-14 (Table 21.2.2)***

3. Moment Capacity Check

$$A_{st} = A_{v,vertical} \frac{l_w}{s_{l,provided}} = 2 \times 0.31 \times \frac{216}{18} = 7.44 \text{ in.}^4$$

$$T = A_{st} \times f_y \left(\frac{l_w - c}{l_w}\right) = 7.44 \times 60 \times \left(\frac{216 - 19.8}{216}\right) = 405 \text{ kips}$$

Taking into account the applied axial force and summing force moments about the compression force (C), the moment capacity can be computed as follows:

$$M_n = T\left(\frac{l_w}{2}\right) + N_u\left(\frac{l_w - c}{2}\right) = 405\left(\frac{216}{2}\right) + 207\left(\frac{216 - 19.8}{2}\right) = 64{,}000 \text{ kips-in.} = 5{,}340 \text{ kips-ft}$$

$$\phi M_n = 0.9 \times 5{,}340 = 4{,}800 \text{ kips-ft} > M_u = 4{,}670 \text{ kips-ft}$$

Since ϕM_n is greater than M_u, the wall has adequate flexural strength.

To further confirm the moment capacity is adequate with detailed consideration for the axial compression, an interaction diagram using spColumn can be created easily as shown below for the wall section. The location of the neutral axis, maximum tensile strain, and the phi factor can all be also verified from the spColumn model results output parameters. As can be seen from the interaction diagram a comprehensive view of the wall behavior for any combination of axial force and applied moment.

For a factored axial and moment of 207 kips and 4670 kip-ft the interaction diagram shows a capacity factor of 1.139 (ϕM_n = 5,320 kip-ft for $\phi P_n = P_u$), see Figures 11 and 12.

4. Shear Capacity Check

$$V_u = 35 + 32 + 26 + 18 + 10 = 121 \text{ kips}$$

$$V_c = \text{lesser of} \begin{Bmatrix} 3.3 \times \lambda \times \sqrt{f_c^{'}} \times h \times d + \dfrac{N_u \times d}{4 \times l_w} & \text{(d)} \\ \left[0.6 \times \lambda \times \sqrt{f_c^{'}} + \dfrac{l_w \left(1.25 \times \lambda \times \sqrt{f_c^{'}} + 0.2 \dfrac{N_u}{l_w \times h} \right)}{\dfrac{M_u}{V_u} - \dfrac{l_w}{2}} \right] \times h \times d & \text{(e)} \end{Bmatrix}$$

ACI 318-14 (Table 11.5.4.6)

$$V_c = \text{lesser of} \begin{Bmatrix} 3.3 \times 1.0 \times \sqrt{4,000} \times 10 \times 173 + \dfrac{207,000 \times 173}{4 \times 216} \\ \left[0.6 \times 1.0 \times \sqrt{4,000} + \dfrac{216 \times \left(1.25 \times 1.0 \times \sqrt{4,000} + 0.2 \dfrac{207,000}{216 \times 10} \right)}{\dfrac{3,580}{121} - \dfrac{216}{2}} \right] \times 10 \times 173 \end{Bmatrix}$$

$$V_c = \text{lesser of} \begin{Bmatrix} 402 \text{ kips} \\ 214 \text{ kips} \end{Bmatrix} = 214 \text{ kips}$$

Where M_u/V_u ratio used in equation (e) was calculated at the critical section above the base of the wall (see Figure 1).

$$\text{distance to the critical section} = \text{smaller of} \begin{Bmatrix} \dfrac{l_w}{2} \\ \dfrac{h_w}{2} \\ \text{one story height} \end{Bmatrix}$$

ACI 318-14 (11.5.4.7)

$$\text{distance to the critical section} = \text{smaller of} \begin{Bmatrix} \dfrac{18}{2} = 9 \text{ ft} \\ \dfrac{54}{2} = 27 \text{ ft} \\ 12 \text{ ft} \end{Bmatrix} = 9 \text{ ft}$$

The factored moment at the ultimate section is equals to:

$$M_u = M_{u,base} - V_{u,base} \times \frac{l_w}{2} = 4,670 - 121 \times 9 = 3,580 \text{ kip-ft}$$

$$\phi V_c = \phi \times V_c = 0.75 \times 214 = 161 \text{ kips}$$

Where $\phi = 0.75$ for shear **_ACI 318-14 (Table 21.2.1)_**

$\phi V_c = 161\,\text{kips} > V_u = 121\,\text{kips}$

Thus, it is not required to calculate the additional shear strength provided by the horizontal reinforcement (V_s)

$0.5 \times \phi V_c = 80.5\,\text{kips} < V_u = 121\,\text{kips}$

Since $0.5\phi V_c$ is less than V_u, ρ_l shall be at least the greater of Equation 11.6.2 in the Code and 0.0025 but need not to exceed ρ_t required by Equation 11.5.4.8. and ρ_t shall be at least 0.0025. **_ACI 318-14 (11.6.2)_**

(Those requirements were checked in step 1).

5. Shear Wall Analysis and Design – spWall Software

spWall is a program for the analysis and design of reinforced concrete shear walls, tilt-up walls, precast wall and insulate concrete form (ICF) walls. It uses a graphical interface that enables the user to easily generate complex wall models. Graphical user interface is provided for:

- Wall geometry (including any number of openings and stiffeners)
- Material properties including cracking coefficients
- Wall loads (point, line, and area),
- Support conditions (including translational and rotational spring supports)

spWall uses the Finite Element Method for the structural modeling, analysis, and design of slender and non-slender reinforced concrete walls subject to static loading conditions. The wall is idealized as a mesh of rectangular plate elements and straight line stiffener elements. Walls of irregular geometry are idealized to conform to geometry with rectangular boundaries. Plate and stiffener properties can vary from one element to another but are assumed by the program to be uniform within each element.

Six degrees of freedom exist at each node: three translations and three rotations relating to the three Cartesian axes. An external load can exist in the direction of each of the degrees of freedom. Sufficient number of nodal degrees of freedom should be restrained in order to achieve stability of the model. The program assembles the global stiffness matrix and load vectors for the finite element model. Then, it solves the equilibrium equations to obtain deflections and rotations at each node. Finally, the program calculates the internal forces and internal moments in each element. At the user's option, the program can perform second order analysis. In this case, the program takes into account the effect of in-plane forces on the out-of-plane deflection with any number of openings and stiffeners.

In spWall, the required flexural reinforcement is computed based on the selected design standard (ACI 318-14 is used in this example), and the user can specify one or two layers of shear wall reinforcement. In stiffeners and boundary elements, spWall calculates the required shear and torsion steel reinforcement. Shear wall concrete strength (in-plane and out-of-plane) is calculated for the applied loads and compared with the code permissible shear capacity.

For illustration and comparison purposes, the following figures provide a sample of the input modules and results obtained from an spWall model created for the reinforced concrete shear wall in this example.

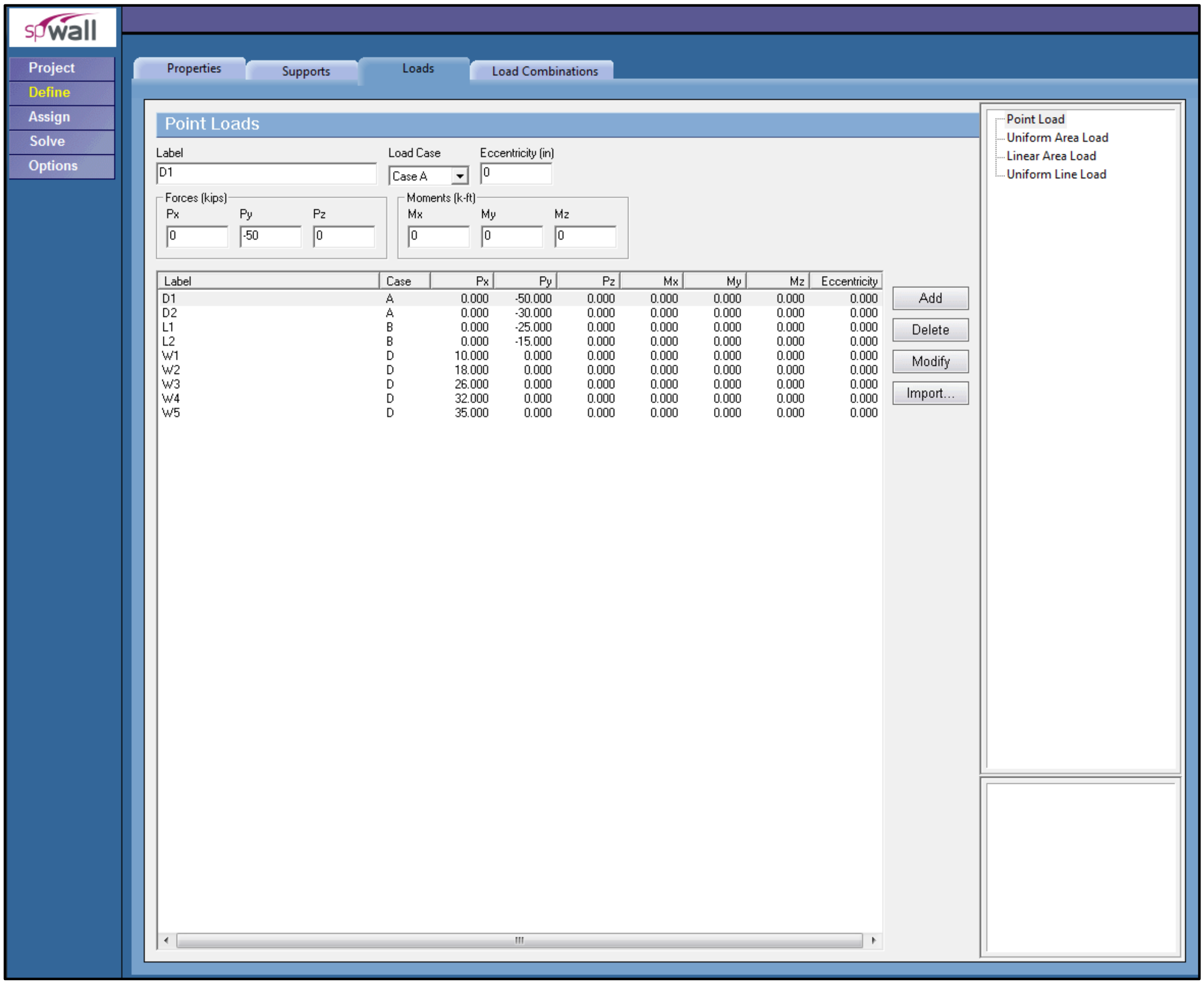


Figure 2 –Defining Loads for Shear Wall (spWall)

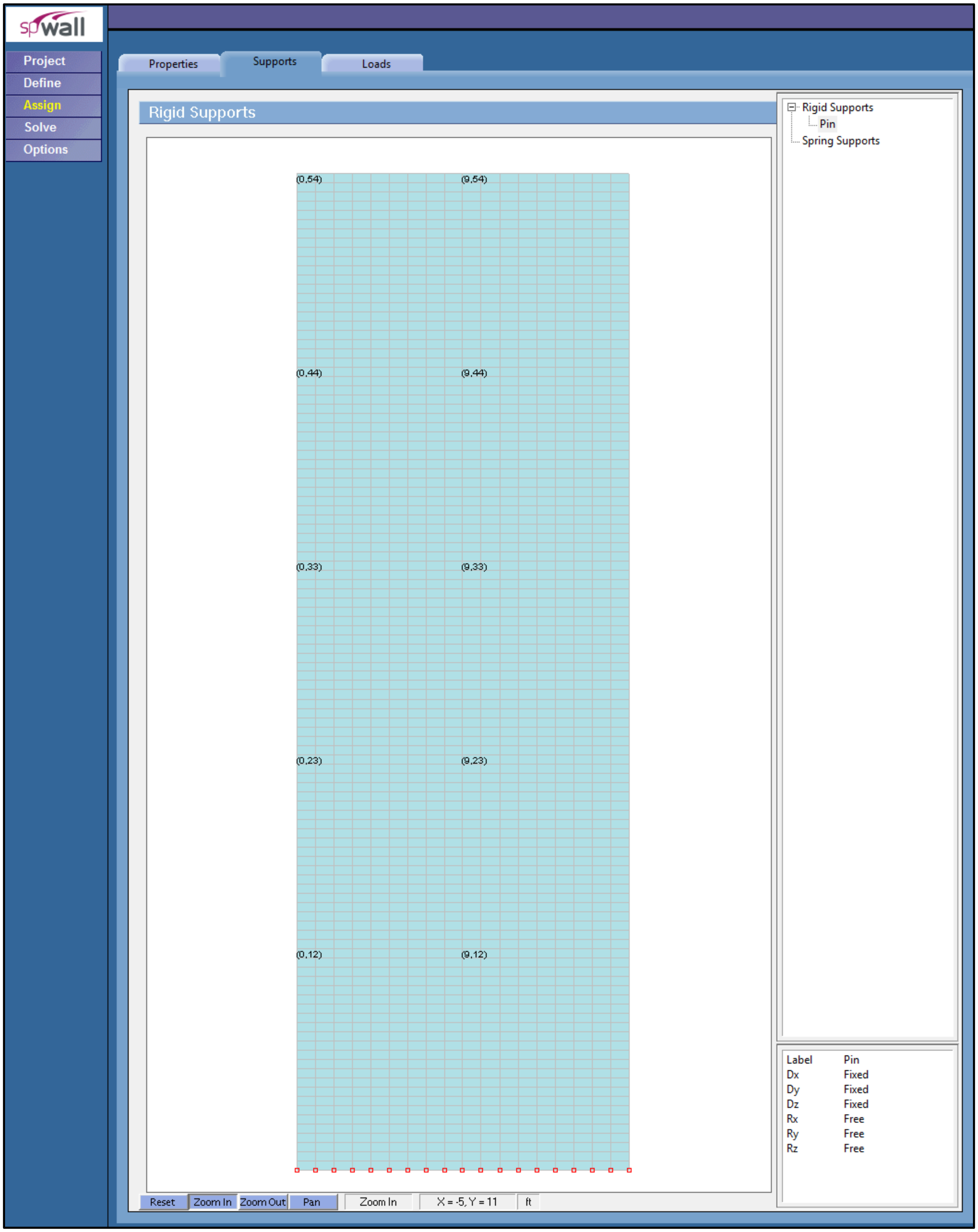


Figure 3 – Assigning Boundary Conditions for Shear Wall (spWall)

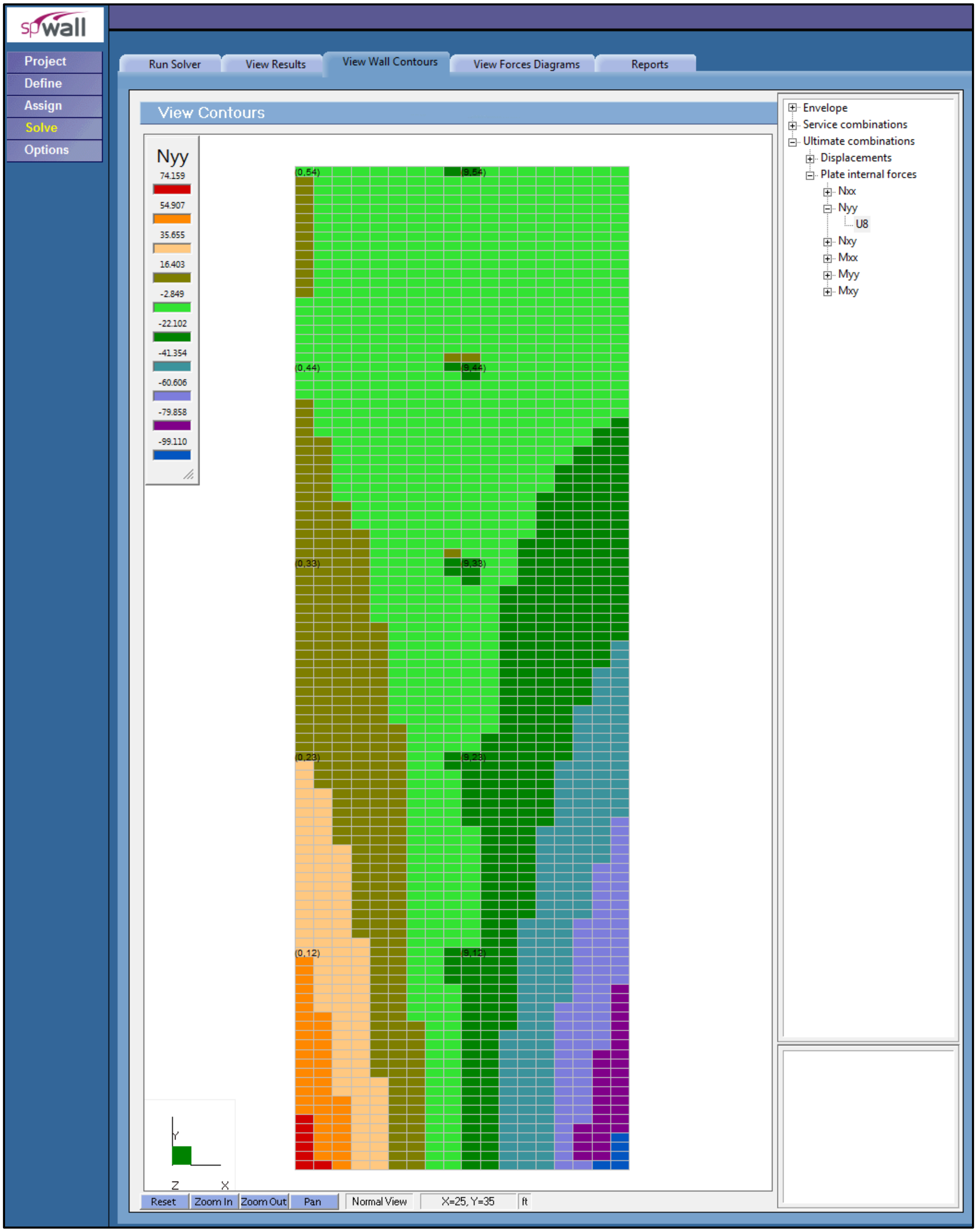


Figure 4 –Factored Axial Forces Contour Normal to Shear Wall Cross-Section (spWall)

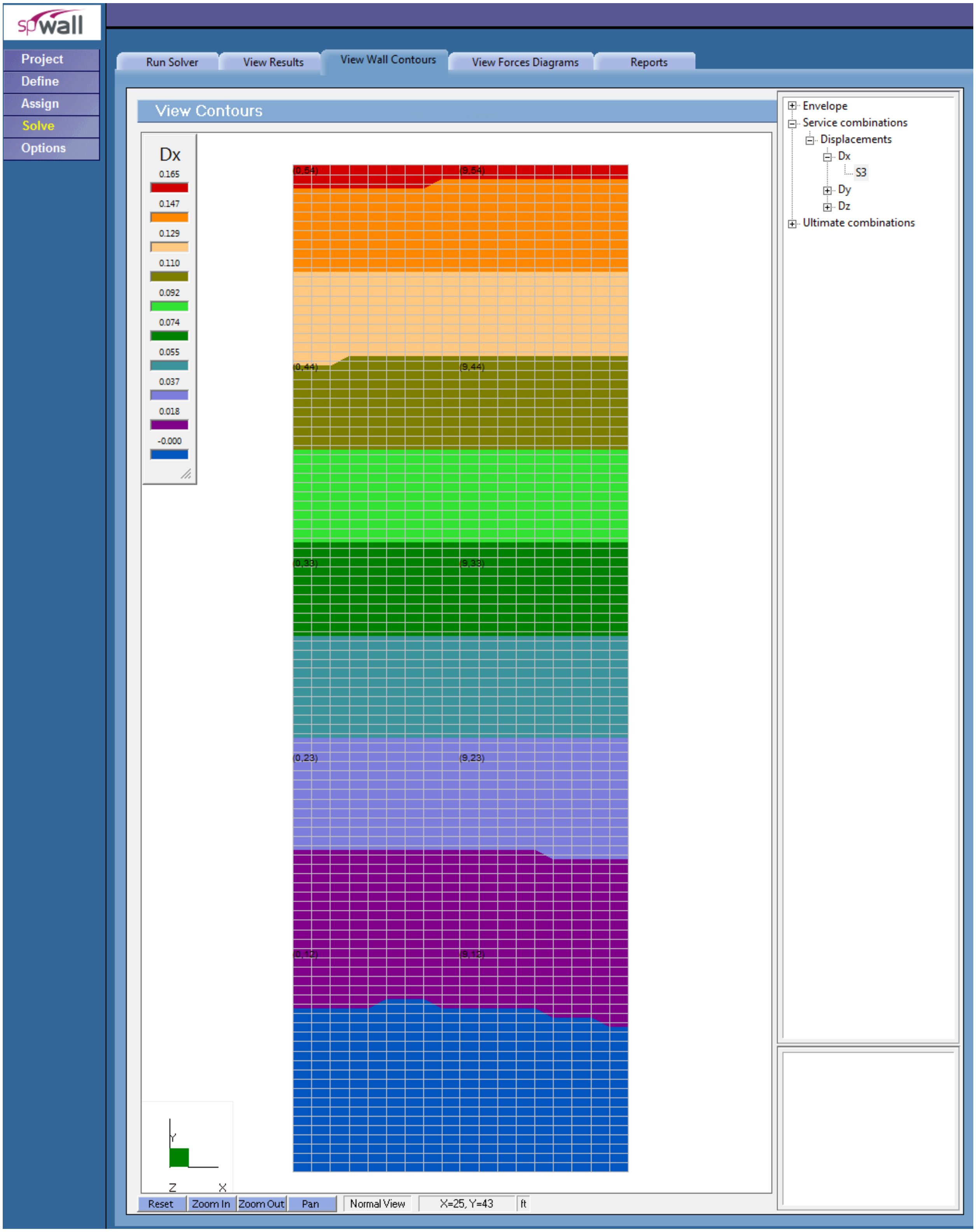


Figure 5 – Shear Wall Lateral Displacement Contour (spWall)

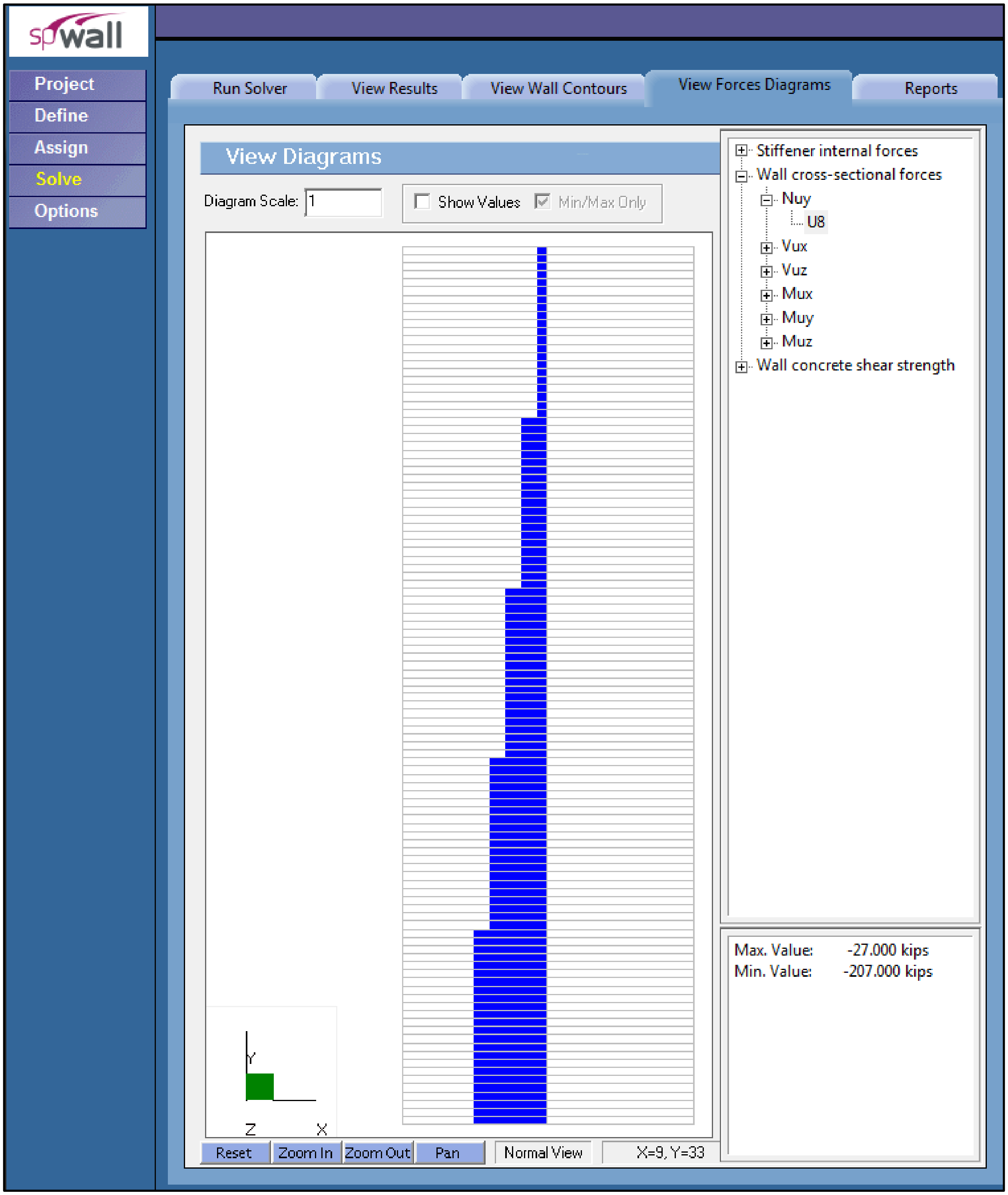


Figure 6 – Shear Wall Axial Load Diagram (spWall)

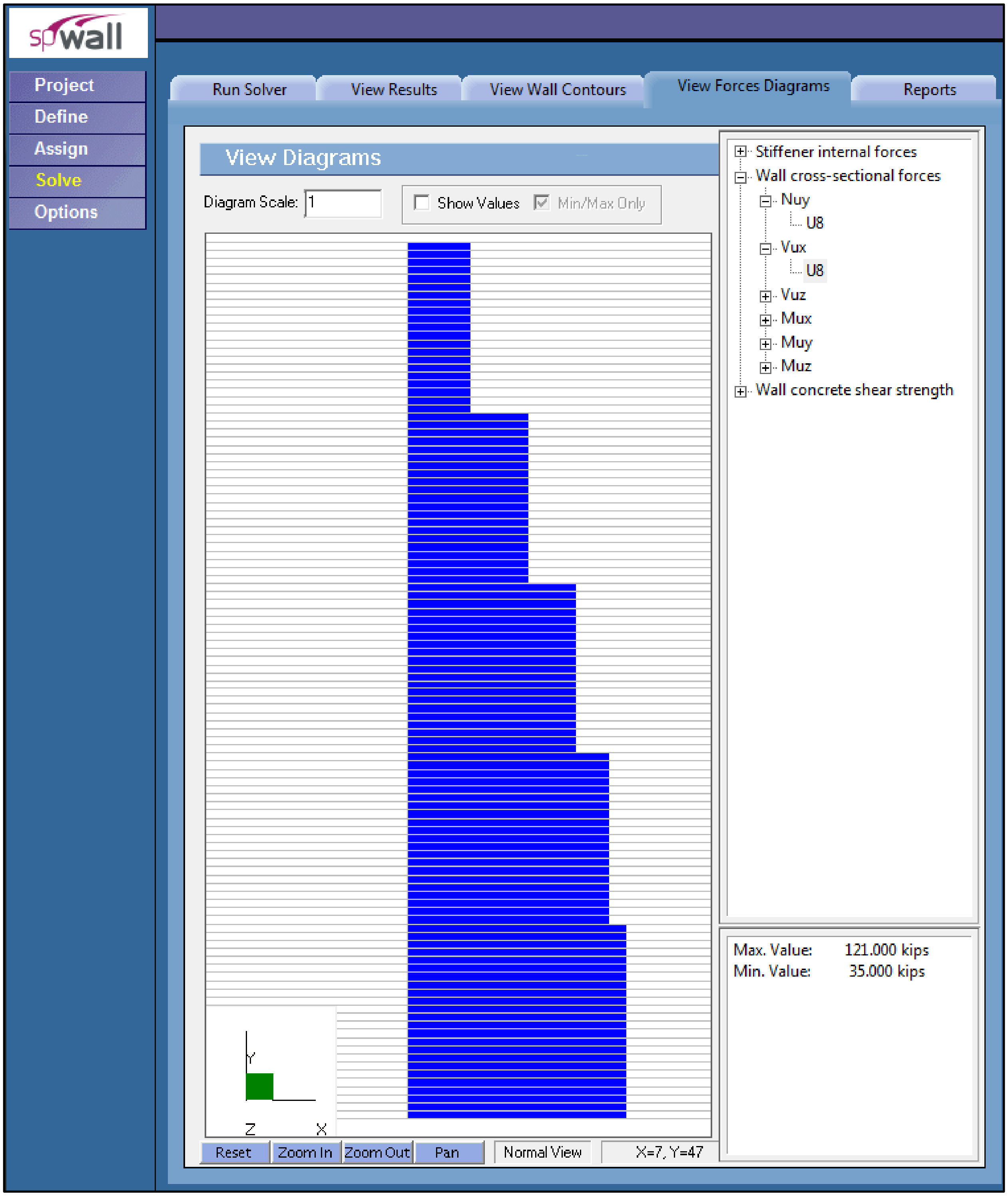


Figure 7 – In-plane Shear Diagram (spWall)

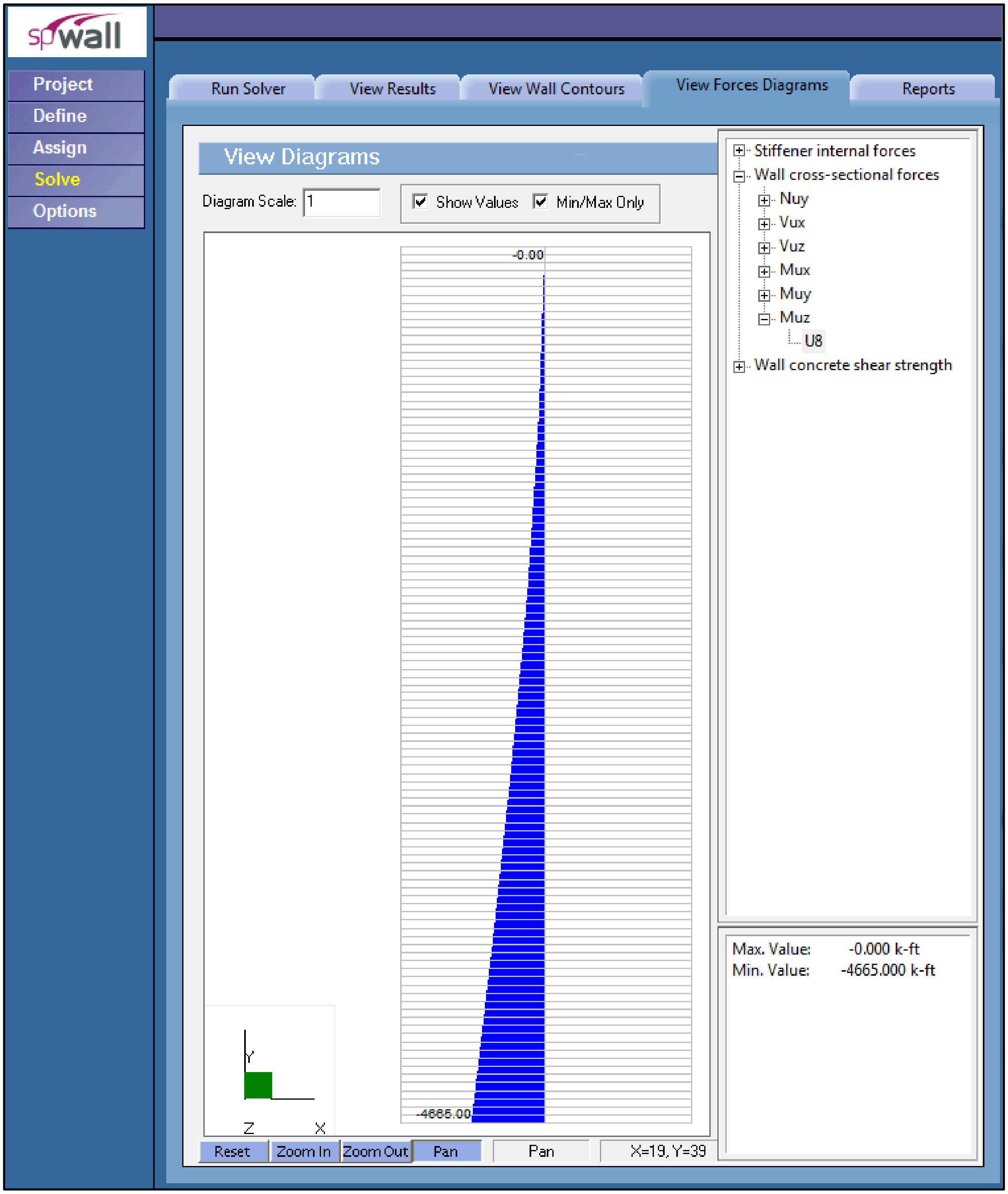


Figure 8 – Shear Wall Moment Diagram (spWall)

```
STRUCTUREPOINT - spWall v5.01 (TM)                                              08-09-2017, 09:25:21 AM
Licensed to: StructurePoint, License ID: 66184-1055153-4-2C6B6-2C6B6
C:\TSDA\Structural Wall Under Lateral Load\Structural Wall.wal                                   Page 1

Envelope | Plate reinforcement
==============================

  Coordinate System:  Global
  ==================

  Units:
  ======
  Total required area of steel (As): in^2/ft
  Bending moment (Mu): k-ft/ft, axial force (Nu): klf


  Elem Curtains  Direction      Mu (x/y)      Nu (x/y)  Ld_combo  As (x/y)   ro(%)  Tie
  ---- -------- ---------- ------------ ------------ -------- ---------- ------ ---
     1        2 Horizontal 0.0000e+000  2.9550e+001 U8        5.53e-001  0.46
                  Vertical 0.0000e+000  7.7378e+001 U8        1.45e+000  1.21
     2        2 Horizontal 0.0000e+000  1.8772e+001 U8        3.51e-001  0.29
                  Vertical 0.0000e+000  7.3781e+001 U8        1.38e+000  1.15
     3        2 Horizontal 0.0000e+000  1.5581e+001 U8        2.91e-001  0.24
                  Vertical 0.0000e+000  5.4554e+001 U8        1.02e+000  0.85
     4        2 Horizontal 0.0000e+000  1.2902e+001 U8        2.41e-001  0.20
                  Vertical 0.0000e+000  4.2835e+001 U8        8.01e-001  0.67
     5        2 Horizontal 0.0000e+000  1.0669e+001 U8        2.40e-001  0.20
                  Vertical 0.0000e+000  3.2675e+001 U8        6.11e-001  0.51
     6        2 Horizontal 0.0000e+000  8.7408e+000 U8        2.40e-001  0.20
                  Vertical 0.0000e+000  2.3359e+001 U8        4.37e-001  0.36
     7        2 Horizontal 0.0000e+000  7.0193e+000 U8        2.40e-001  0.20
                  Vertical 0.0000e+000  1.4611e+001 U8        2.73e-001  0.23
     8        2 Horizontal 0.0000e+000  5.4510e+000 U8        2.40e-001  0.20
                  Vertical 0.0000e+000  6.2406e+000 U8        1.44e-001  0.12
     9        2 Horizontal 0.0000e+000  2.6129e+000 U8        2.40e-001  0.20
                  Vertical 0.0000e+000 -1.2546e+001 U8        1.44e-001  0.12
    10        2 Horizontal 0.0000e+000 -8.4802e+000 U8        2.40e-001  0.20
                  Vertical 0.0000e+000 -2.0955e+001 U8        1.44e-001  0.12
    11        2 Horizontal 0.0000e+000 -1.0370e+001 U8        2.40e-001  0.20
                  Vertical 0.0000e+000 -2.9458e+001 U8        1.44e-001  0.12
    12        2 Horizontal 0.0000e+000 -1.2361e+001 U8        2.40e-001  0.20
                  Vertical 0.0000e+000 -3.8160e+001 U8        1.44e-001  0.12
    13        2 Horizontal 0.0000e+000 -1.4490e+001 U8        2.40e-001  0.20
                  Vertical 0.0000e+000 -4.7212e+001 U8        1.44e-001  0.12
    14        2 Horizontal 0.0000e+000 -1.6819e+001 U8        2.40e-001  0.20
                  Vertical 0.0000e+000 -5.6863e+001 U8        1.44e-001  0.12
    15        2 Horizontal 0.0000e+000 -1.9473e+001 U8        2.40e-001  0.20
                  Vertical 0.0000e+000 -6.7480e+001 U8        1.44e-001  0.12
    16        2 Horizontal 0.0000e+000 -2.2634e+001 U8        2.40e-001  0.20
                  Vertical 0.0000e+000 -8.0022e+001 U8        1.44e-001  0.12
    17        2 Horizontal 0.0000e+000 -2.6373e+001 U8        2.40e-001  0.20
                  Vertical 0.0000e+000 -1.0247e+002 U8        1.44e-001  0.12
    18        2 Horizontal 0.0000e+000 -4.0107e+001 U8        2.40e-001  0.20
                  Vertical 0.0000e+000 -1.0437e+002 U8        1.44e-001  0.12
```

Elements along the wall base

$\sum A_{s,vertical}$ = 7.56 in.^{2}

Figure 9 – Shear Wall Vertical Reinforcement (spWall)

```
STRUCTUREPOINT - spWall v5.01 (TM)                                              08-09-2017, 09:29:15 AM
Licensed to: StructurePoint, License ID: 66184-1055153-4-2C6B6-2C6B6
C:\TSDA\Structural Wall Under Lateral Load\Structural Wall.wal                                   Page 1

Envelope | Wall concrete shear strength | In-plane shear
=======================================================

  Coordinate System:  Global
  ==================

  Units:
  ======
  Y-coordinate: ft
   (+) Horizontal cross-section above Y-coordinate
   (-) Horizontal cross-section below Y-coordinate
  Force (Nuy, Vux): kips
  Moment (Muz): k-ft
  Wall concrete shear strength (Vcx): kips

  __Cross-section__ _____________Cross-sectional Forces____________ __Strength__
  No.  Y-coordinate Ld_combo         Nuy          Muz          Vux      Phi*Vcx
  ---- ------------ -------- ------------ ------------ ------------ ------------
    1+        0.000 U8       -2.0700e+002 -4.6650e+003  1.2100e+002  1.6393e+002 #
   19+        9.000 U8       -2.0700e+002 -3.5760e+003  1.2100e+002  1.6393e+002 #

  Notes:
  # - Shear force Vux exceeds 0.5*Phi*Vcx
```

Figure 10 – Concrete Shear Strength and Shear Wall Cross-Sectional Forces (spWall)

6. Design Results Comparison and Conclusions

Table 1 – Comparison of Shear Wall Analysis and Design Results							
Solution	Wall Cross-Sectional Forces				Strength	Required A_s	Provided A_s
	M_u (kip-ft)	N_u (kips)	V_u (kips)	$M_{u@critical\ Section}$ (kip-ft)	ϕV_c (kips)	$A_{s,vertical}$ (in.^{2})	$A_{s,vertical}$ (in.^{2})
Hand	4,670	207	121	3,580	161	Governed by Min.	7.44
Reference	4,670	207	121	3,580	161	Governed by Min.	7.44
spWall	4,665	207	121	3,576	164	Governed by Min.	7.56

The results of all the hand calculations and the reference used illustrated above are in precise agreement with the automated exact results obtained from the spWall program. It is worth noting that the minimum area of steel is governed by the minimum reinforcement ratio stipulated by the code. The same can be seen in spWall output for elements 9 through 18.

In the hand calculations and the reference, a simplified procedure to calculate the nominal flexural strength was used (A. E. Cardenas et al.). In this procedure, several broad assumptions are made to avoid tedious detailed calculations:

- All steel in the tension zone yields in tension.
- All steel in the compression zone yields in compression.
- The tension force acts at mid-depth of the tension zone.
- The total compression force (sum of steel and concrete contributions) acts at mid-depth of the compression zone.

To investigate the exact shear wall cross section capacity, a detailed interaction diagram can be easily generated by spColumn conforming 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.

For illustration and comparison purposes, following figures provide a sample of the input and output of the exact results obtained from an spColumn model created for the reinforced concrete shear wall in this example. spColumn calculates the exact values of strain at each layer of steel (in tension and compression zones) with exact location of the total tension and compression forces leading to exact value for nominal and design strengths (axial and flexural strengths).

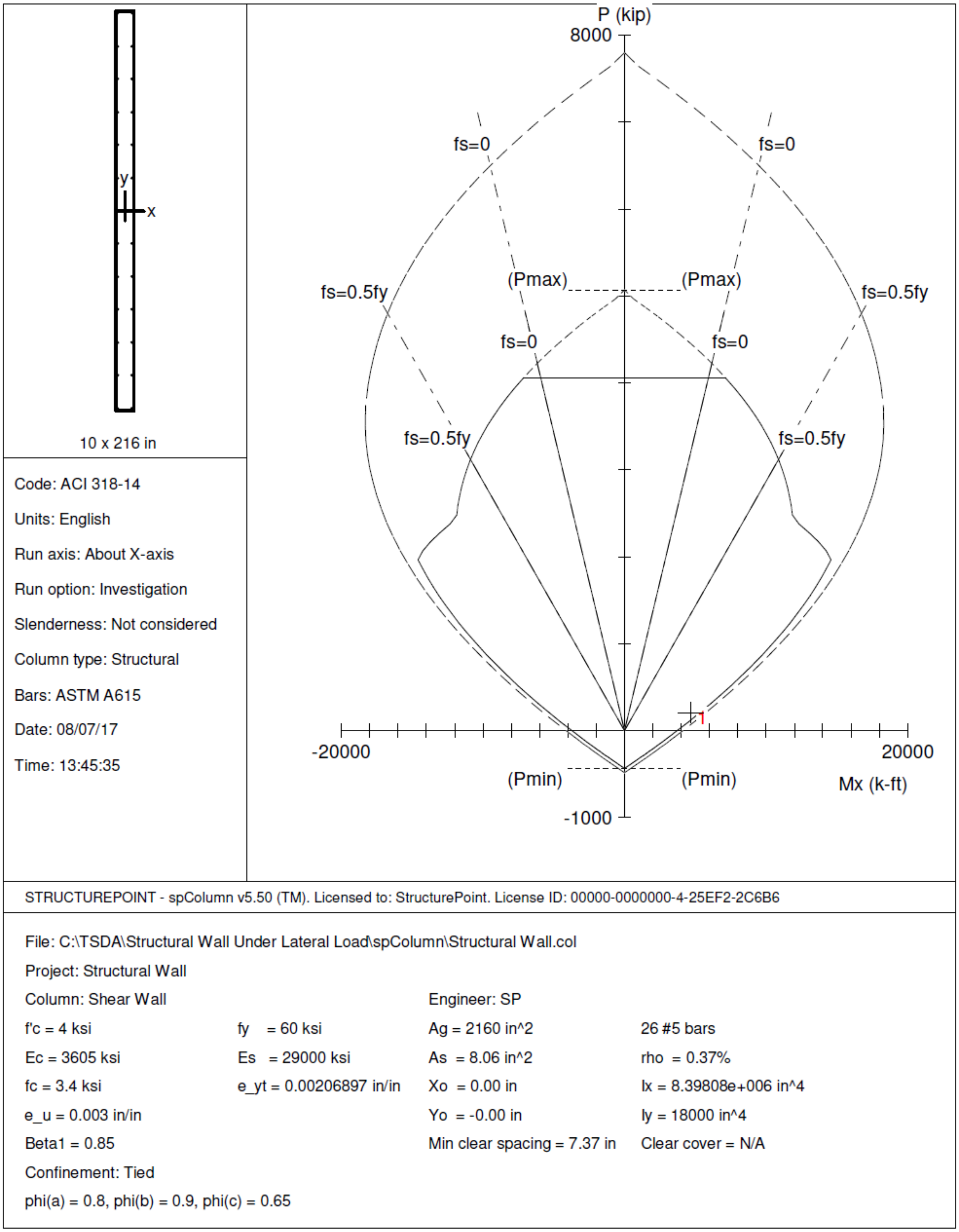


Figure 11 – Shear Wall Interaction Diagram (X-Axis, In-Plane) (spColumn)

```
STRUCTUREPOINT - spColumn v5.50 (TM)                                                                   Page   2
Licensed to: StructurePoint. License ID: 00000-0000000-4-25EF2-2C6B6                                   08/07/17
C:\TSDA\Structural Wall Under Lateral Load\spColumn\Structural Wall.col                                01:45 PM


General Information:
====================
  File Name: C:\TSDA\Structural Wall Under Lateral Load\spColumn\Structural Wall.col
  Project:  Structural Wall
  Column:   Shear Wall                        Engineer: SP
  Code:     ACI 318-14                        Units: English

  Run Option: Investigation                   Slenderness: Not considered
  Run Axis:   X-axis                          Column Type: Structural

Material Properties:
====================
  Concrete: Standard                          Steel: Standard
  f'c    = 4 ksi                              fy     = 60 ksi
  Ec     = 3605 ksi                           Es     = 29000 ksi
  fc     = 3.4 ksi                            Eps_yt = 0.00206897 in/in
  Eps_u = 0.003 in/in
  Beta1 = 0.85

Section:
========
  Exterior Points
    No.     X (in)     Y (in)     No.     X (in)     Y (in)     No.     X (in)     Y (in)
  ----- ---------- ---------- ----- ---------- ---------- ----- ---------- ----------
      1       -5.0     -108.0     2        5.0     -108.0     3        5.0      108.0
      4       -5.0      108.0

  Gross section area, Ag =  2160 in^2
  Ix =  8.39808e+006 in^4                     Iy =  18000 in^4
  rx =  62.3538 in                            ry =  2.88675 in
  Xo =  0 in                                  Yo =  -0 in

Reinforcement:
==============
  Bar Set: ASTM A615
  Size Diam (in) Area (in^2)   Size Diam (in) Area (in^2)   Size Diam (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

  Confinement: Tied; #3 ties with #10 bars,  #4 with larger bars.
  phi(a) = 0.8,  phi(b) = 0.9,  phi(c) = 0.65

  Pattern: Irregular
  Total steel area: As = 8.06 in^2 at rho = 0.37% (Note: rho < 0.50%)
  Minimum clear spacing = 7.37 in

  Area in^2  X (in)   Y (in)  Area in^2  X (in)   Y (in)  Area in^2  X (in)   Y (in)
  --------- -------- -------- --------- -------- -------- --------- -------- --------
       0.31     -4.0    107.0      0.31      4.0    107.0      0.31      4.0     89.2
       0.31      4.0     71.3      0.31      4.0     53.5      0.31      4.0     35.7
       0.31      4.0     17.8      0.31      4.0     -0.0      0.31      4.0    -17.8
       0.31      4.0    -35.7      0.31      4.0    -53.5      0.31      4.0    -71.3
       0.31      4.0    -89.2      0.31      4.0   -107.0      0.31     -4.0   -107.0
       0.31     -4.0    -89.2      0.31     -4.0    -71.3      0.31     -4.0    -53.5
       0.31     -4.0    -35.7      0.31     -4.0    -17.8      0.31     -4.0     -0.0
       0.31     -4.0     17.8      0.31     -4.0     35.7      0.31     -4.0     53.5
       0.31     -4.0     71.3      0.31     -4.0     89.2

STRUCTUREPOINT - spColumn v5.50 (TM)                                                                   Page   3
Licensed to: StructurePoint. License ID: 00000-0000000-4-25EF2-2C6B6                                   08/07/17
C:\TSDA\Structural Wall Under Lateral Load\spColumn\Structural Wall.col                                01:45 PM


Factored Loads and Moments with Corresponding Capacities:
=========================================================
                 Pu          Mux        PhiMnx PhiMn/Mu NA depth Dt depth    eps_t    Phi
  No.           kip         k-ft          k-ft               in       in
  --- ------------ ------------ ------------ -------- -------- -------- -------- ------
    1       207.00      4670.00      5319.18    1.139    20.73   215.00  0.02811  0.900

  *** End of output ***
```

Figure 12 – Load & Moment Capacities Output from spColumn

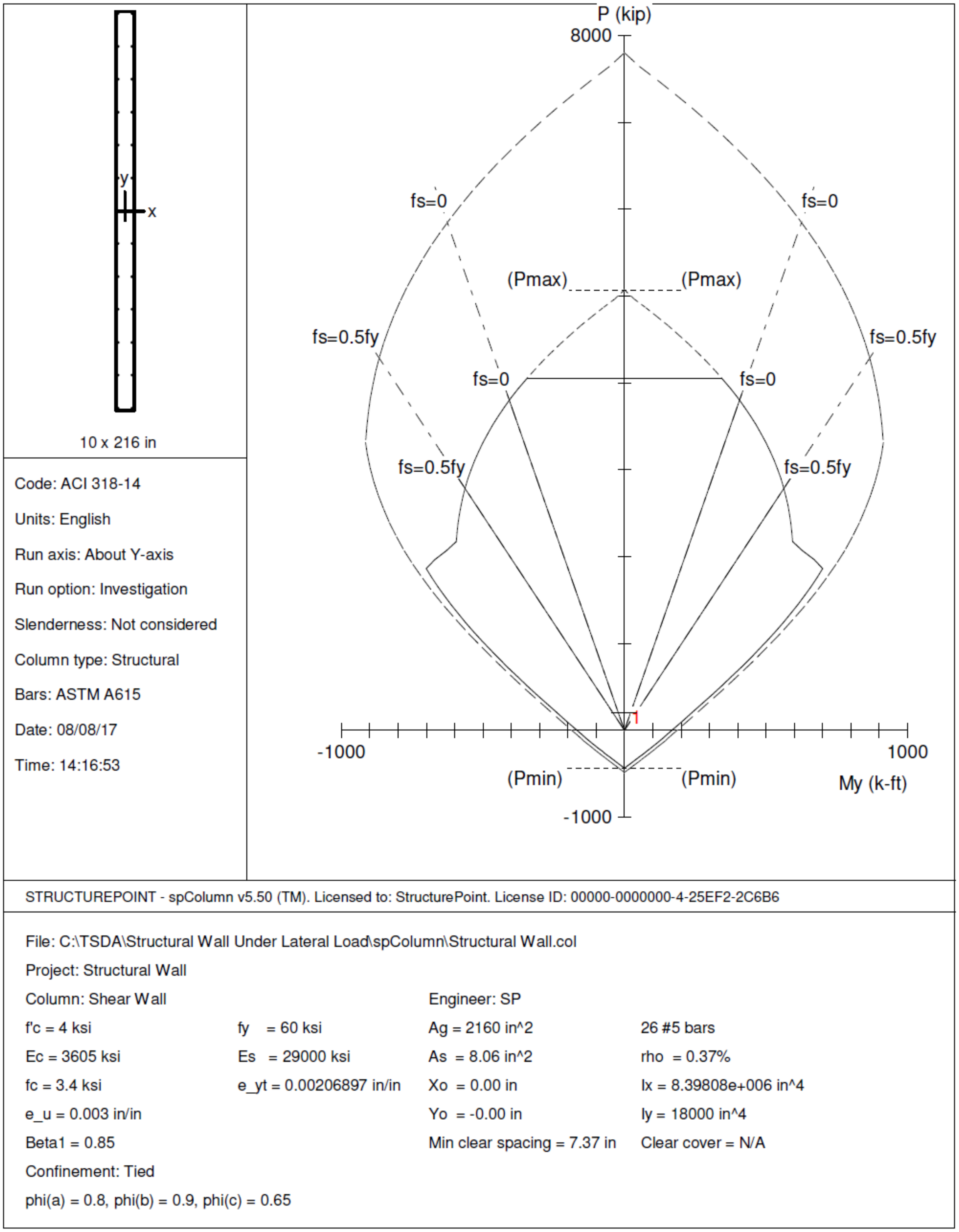


Figure 13 – Shear Wall Interaction Diagram (Y-Axis, Out-of-Plane) (spColumn)

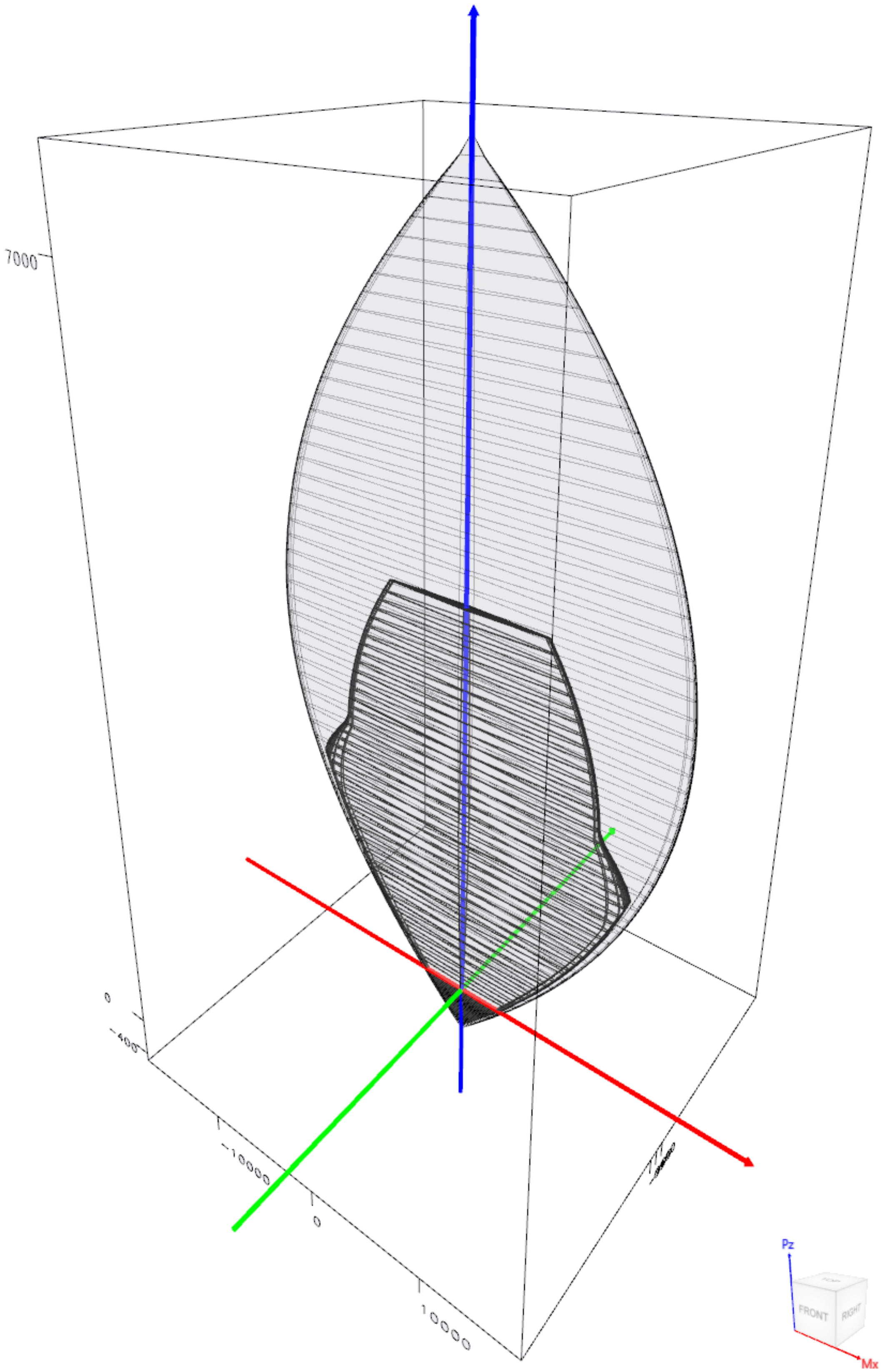


Figure 14 – Wall Section Interaction Diagram – 3D (spColumn)

Using the spColumn results output, further comparison can be made for the shear wall capacity parameters as summarized below:

Table 2 – Comparison of Flexural Capacity Based on Method of Solution				
Solution Method	c, in.	ε_t, in./in.	ϕM_n, kip-ft	$(\text{Calculated/Exact})_{\text{Capacity}}$
Hand	19.80	---	4,670	88%
Reference	19.80	---	4,670	88%
spWall	---	---	5,344*	100%
spColumn	20.73	0.02811	5,319	100%
* Calculated from spWall plate reinforcement by summing the capacity of each element along the wall cross-section				

The last column in the table above compares the hand calculated capacity estimated by approximate methods to the exact values generated by spWall and spColumn. The impact of simplifying assumptions is illustrated in the figure below showing the value of incorporating the exact value and location of steel and concrete strains and forces.

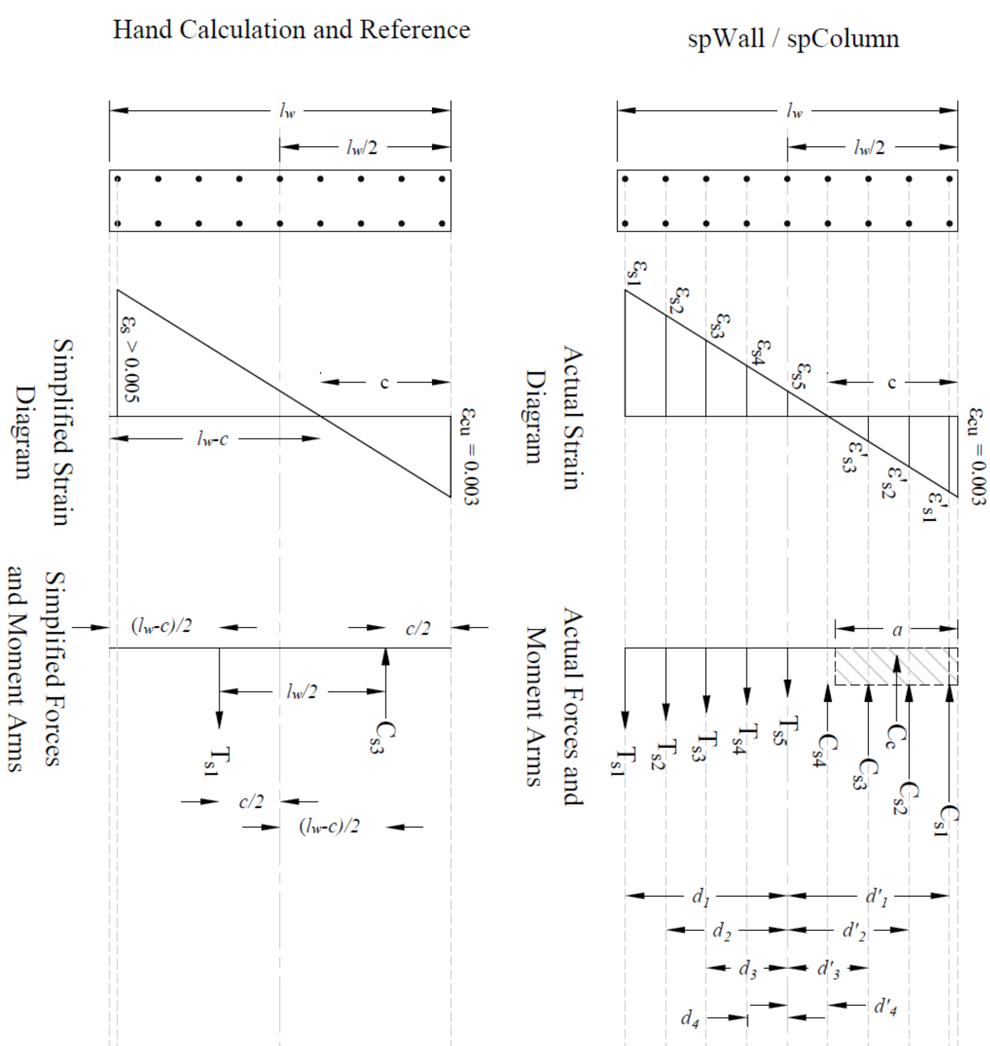


Figure 15 – Strains, Forces, and Moment Arms for simplified and Actual Methods