Insulated Concrete Forms (ICF) Walls Analysis and Design

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Insulating concrete form or insulated concrete form (ICF) is a system of formwork for reinforced concrete usually made with a rigid thermal insulation that stays in place as a permanent interior and exterior substrate for walls, floors, and roofs. The forms are interlocking modular units that are dry-stacked (without mortar) and filled with concrete. The units lock together somewhat like Lego bricks and create a form for the structural walls or floors of a building. ICF construction has become commonplace for both low rise commercial and high performance residential construction as more stringent energy efficiency and natural disaster resistant building codes are adopted. ICFs may be used with frost protected shallow foundations (FPSF). This case study focuses on the design of ICF walls using the engineering software program spWall. The ICF wall under study is a wall in a typical four-story apartment building. The building consists of 92 apartments, 60 one-bedroom apartment and 32 two-bedroom apartments. The concrete floor assembly carried by the wall consists of 2" concrete topping and 8" prestressed hollow core concrete slab. The following figure and design data section and will serve as input for detailed design.

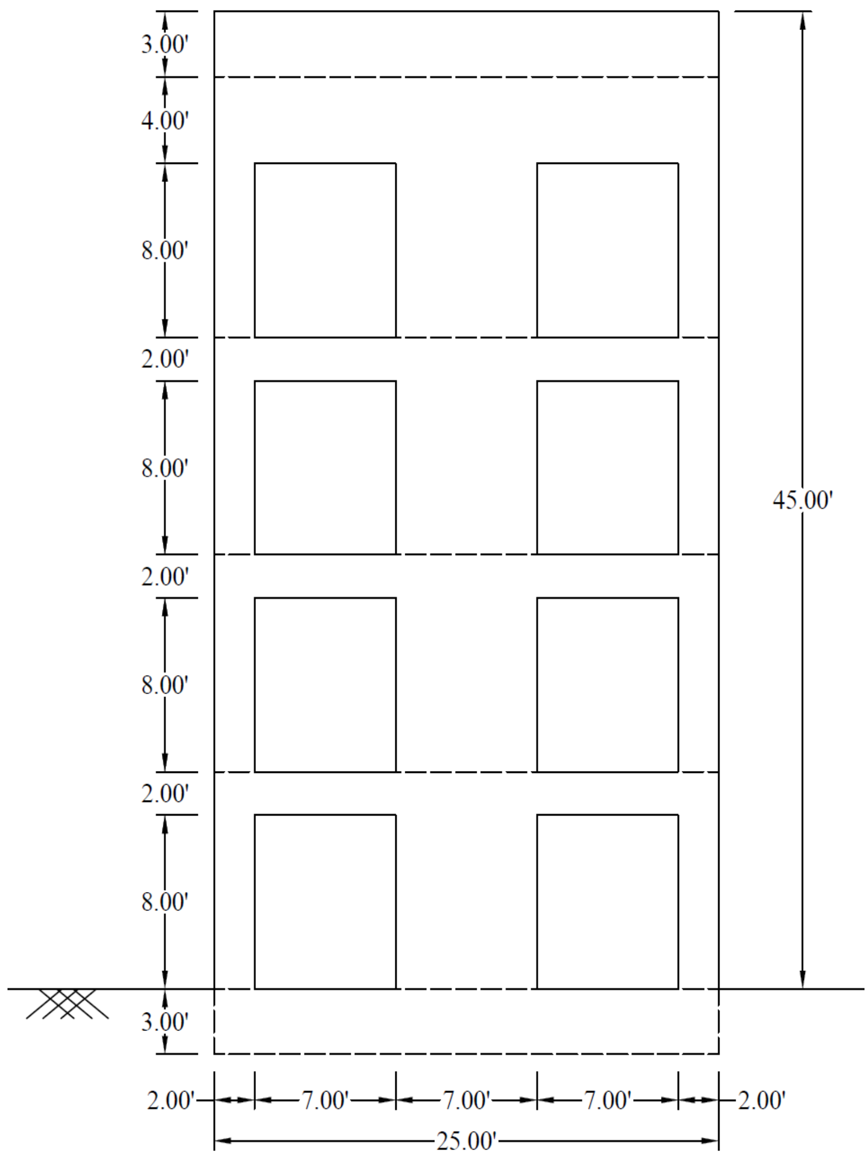


Figure 1 – ICF Wall Elevation

Code

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

Reference

spWall Engineering Software Program Manual v5.01, StucturePoint LLC., 2016

Design Data

Wall Material Properties

f_c' = 4,000 psi

f_y = 60,000 psi

Wall Dimensions

Width = 25 ft

Height = 45 ft

Opening Size = 8 ft x 7 ft

Thickness = 6 in.

Wall Loads

$P_{DL,floor}$ = 1250 lb/ft

$P_{DL,roof}$ = 450 lb/ft

$P_{LL,floor}$ = 600 lb/ft

$P_{LL,roof}$ = 200 lb/ft

W_{wind} = 30 psf

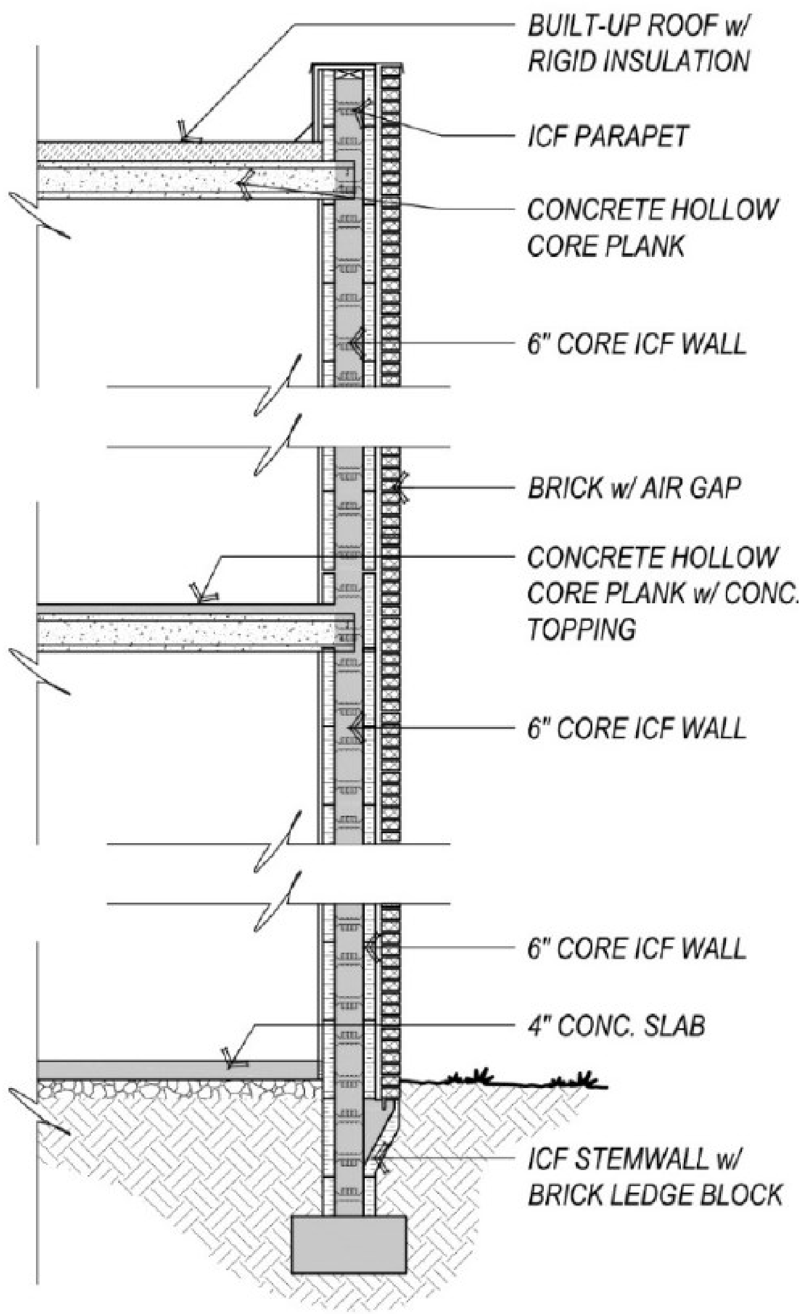


Figure 2 – Wall Architectural Cross-Section

Contents

1. ICF Wall Analysis and Design – spWall Software

spWall is a program for the analysis and design of reinforced concrete shear walls, tilt-up walls, precast walls and Insulated 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)

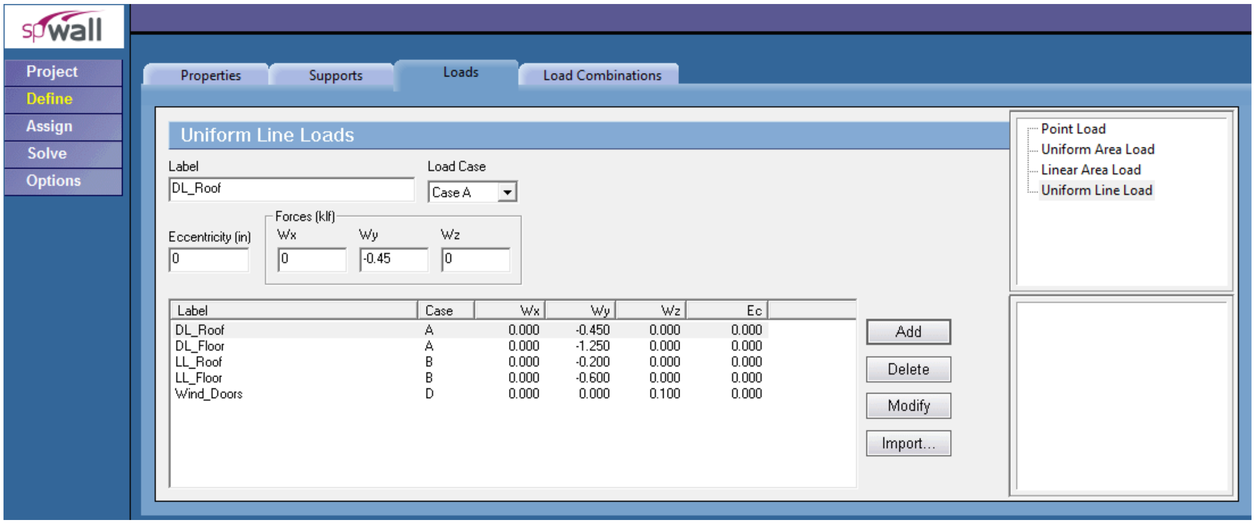
spWall uses the Finite Element Method for the structural modeling, analysis, and design of slender and non-slender reinforced concrete walls subject to static loading conditions. The wall is idealized as a mesh of rectangular plate elements and straight line stiffener elements. Walls of irregular geometry 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 case study), and the user can specify one or two layers of wall reinforcement. In stiffeners and boundary elements, spWall calculates the required shear and torsion steel reinforcement. 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 ICF wall in this case study.

2. Wall Model Input



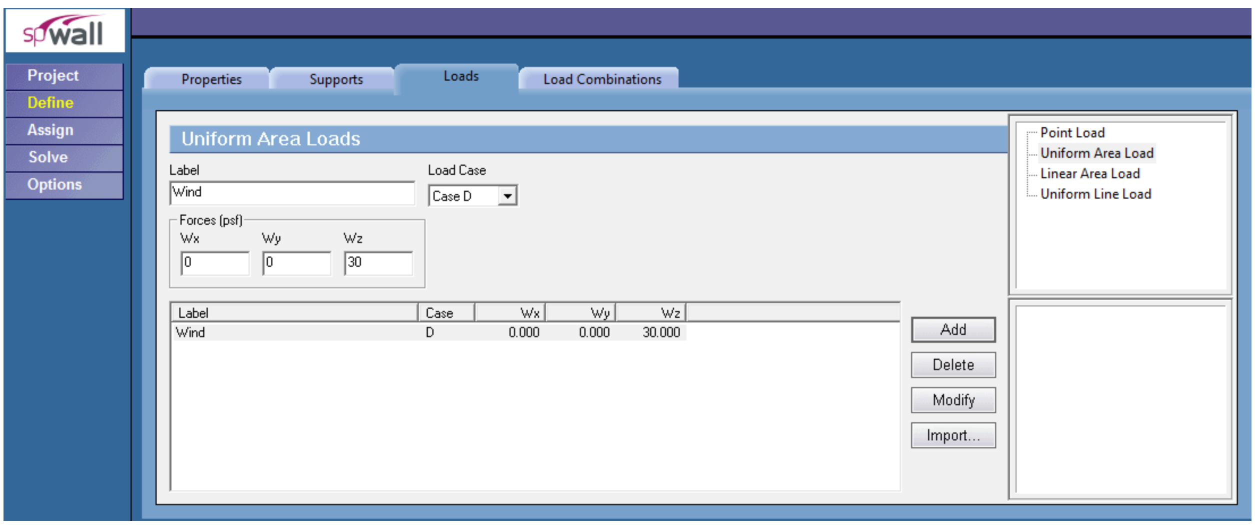


Figure 3 –Defining Wall Loads

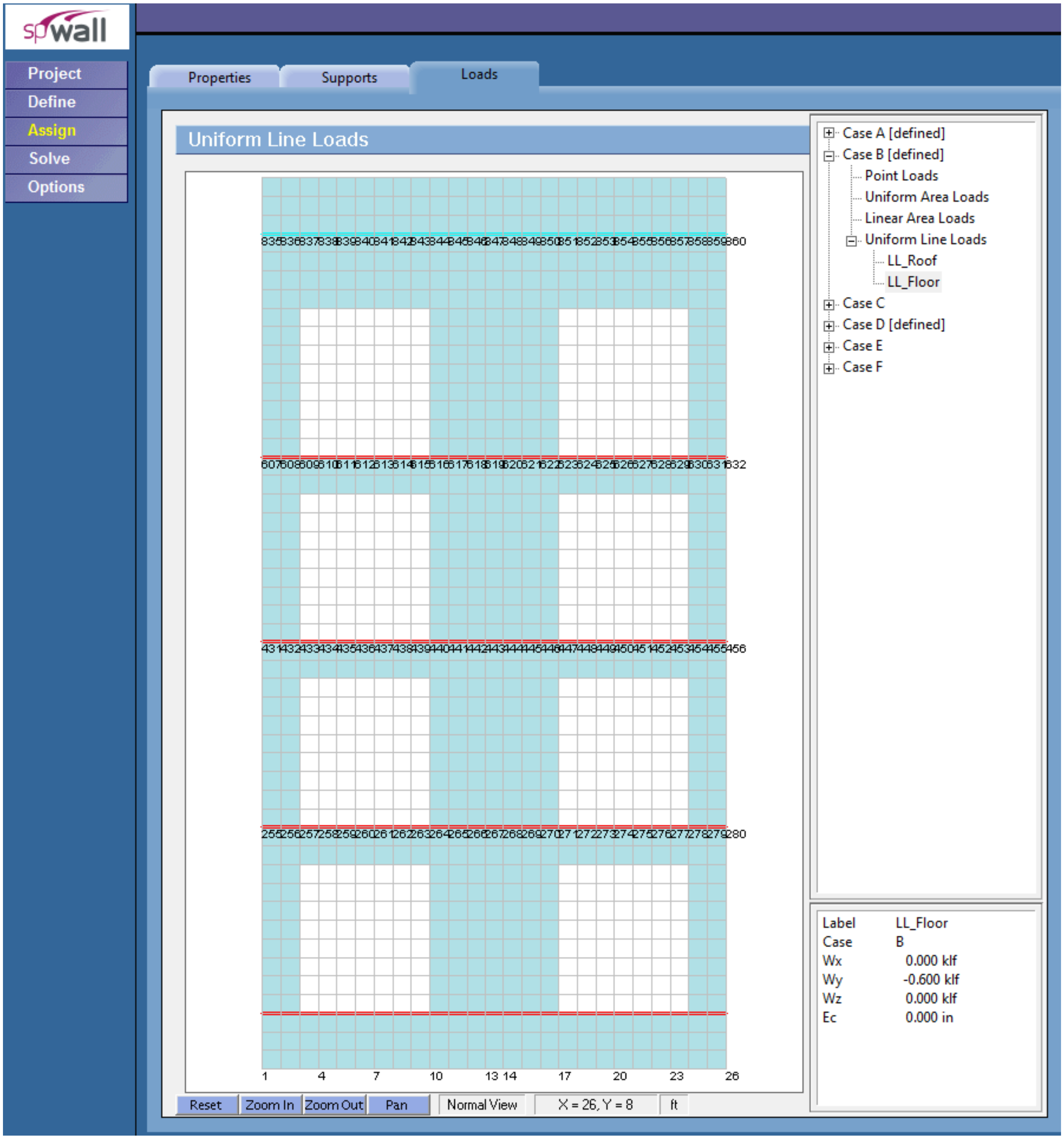


Figure 4 – Assigning Loads

3. Wall Results Contours

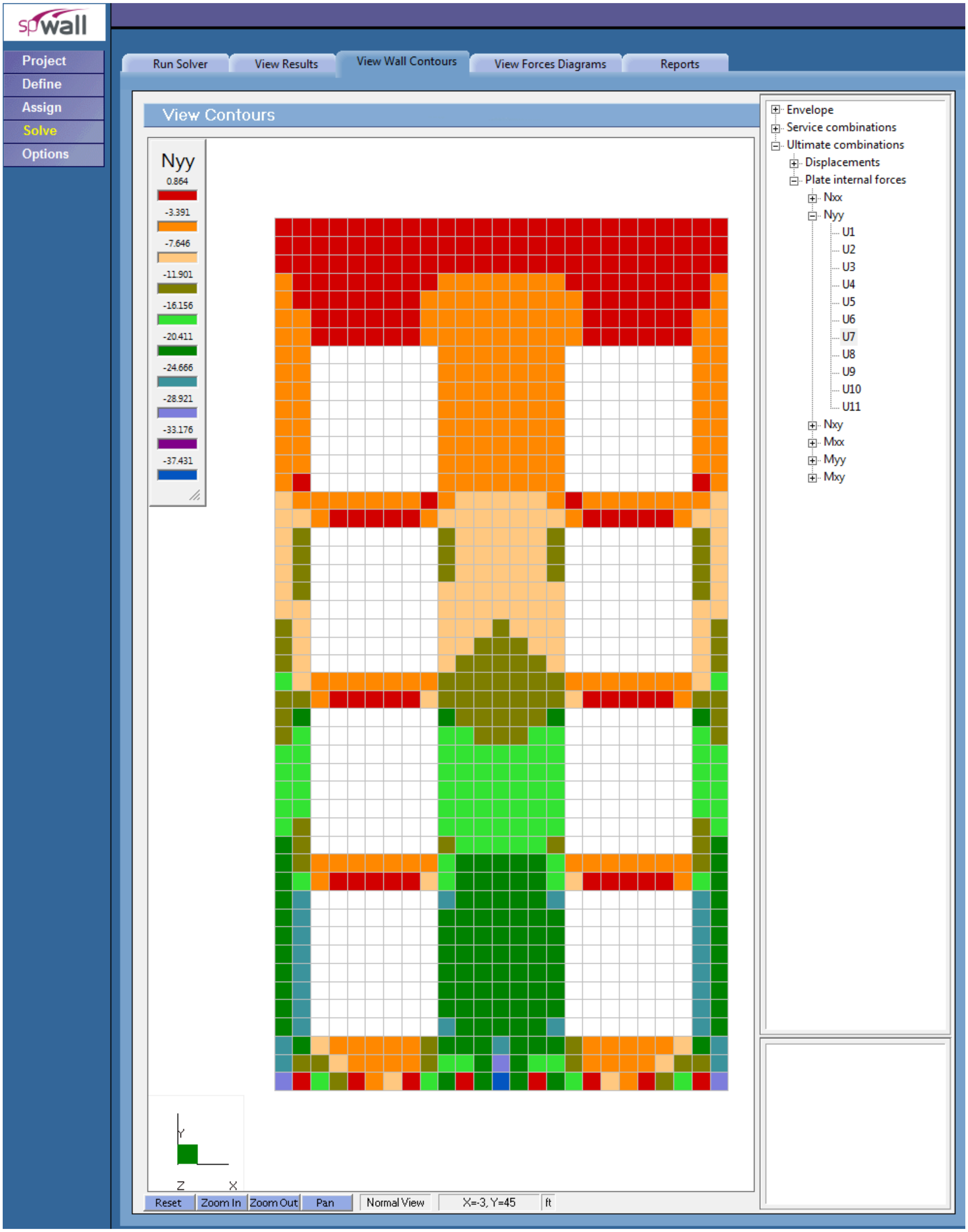


Figure 5 – Factored Axial Forces Contour Normal to Tilt-Up Wall Panel Cross-Section

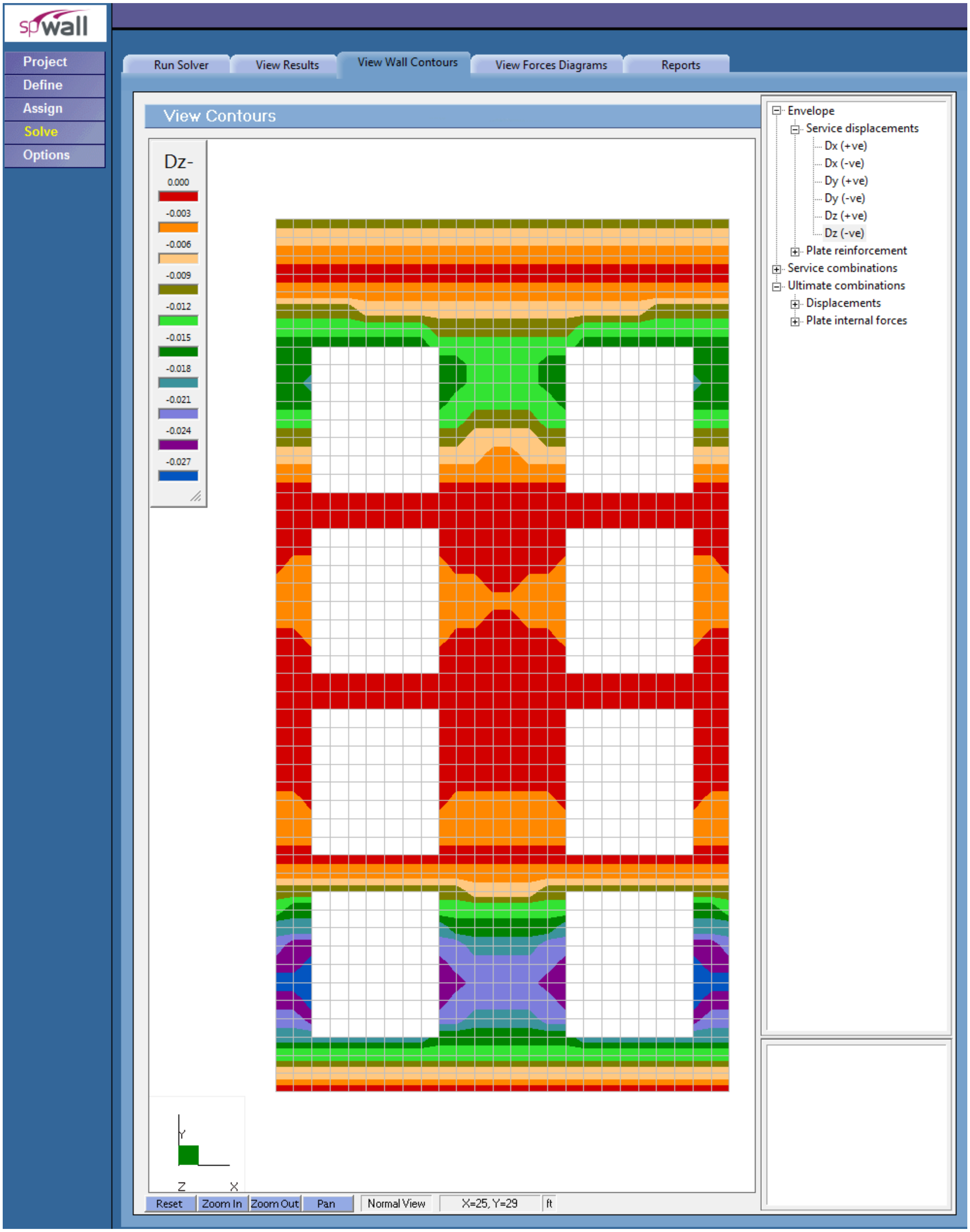


Figure 6 –Lateral Displacement Contour (Out-of-Plane)

4. Wall Cross-Sectional Forces

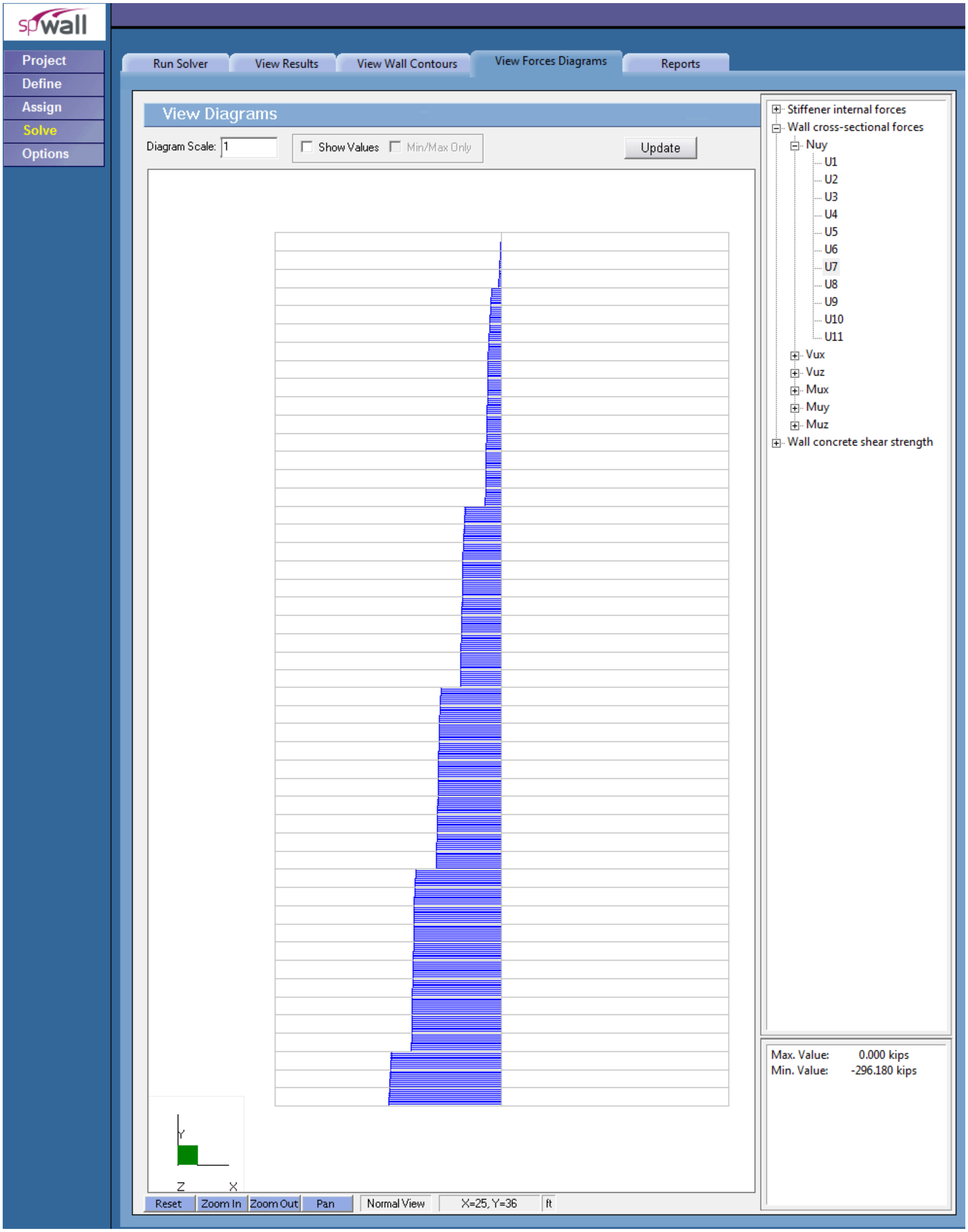


Figure 7 – Axial Load Diagram

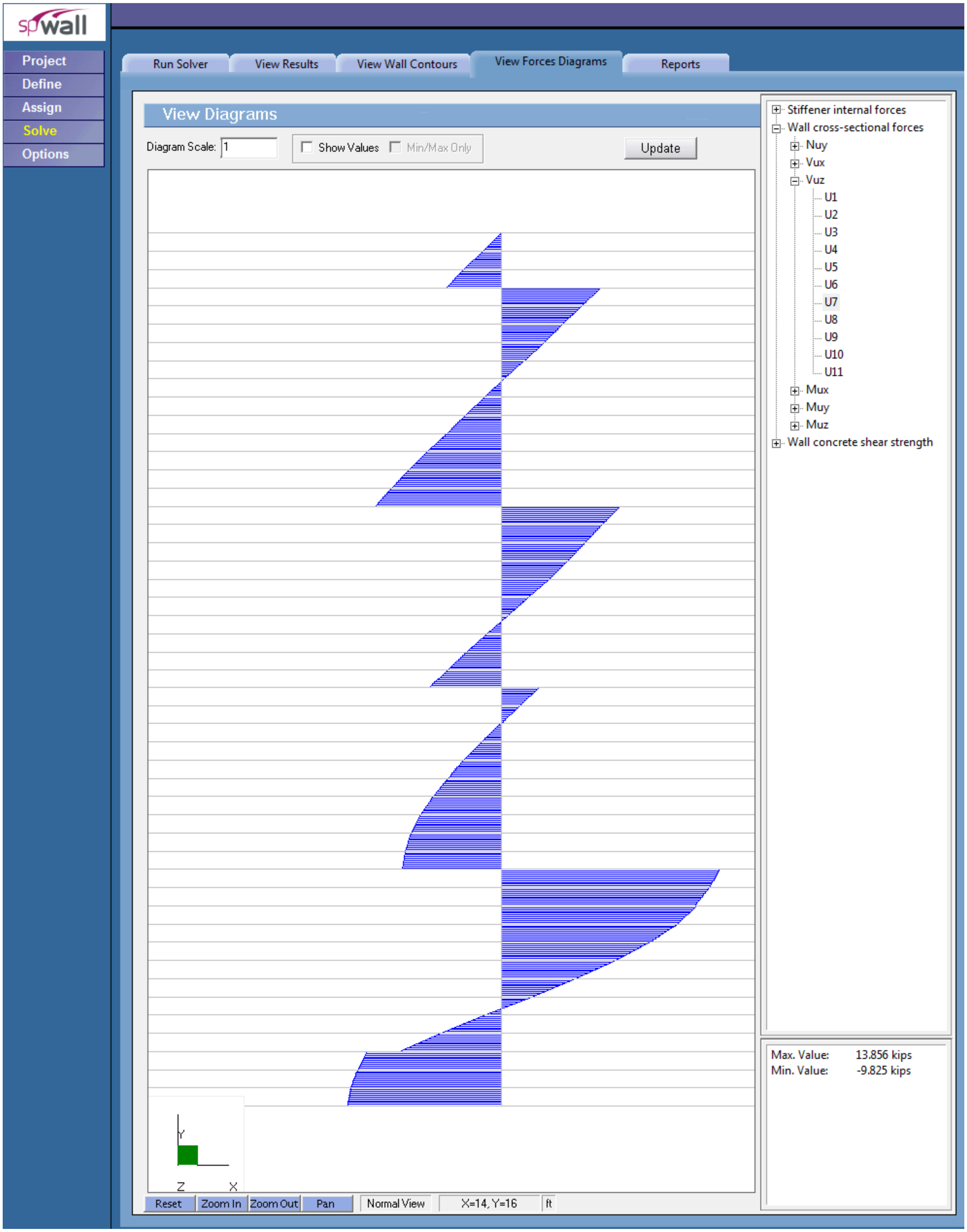


Figure 8 – Out-of-Plane Shear Diagram

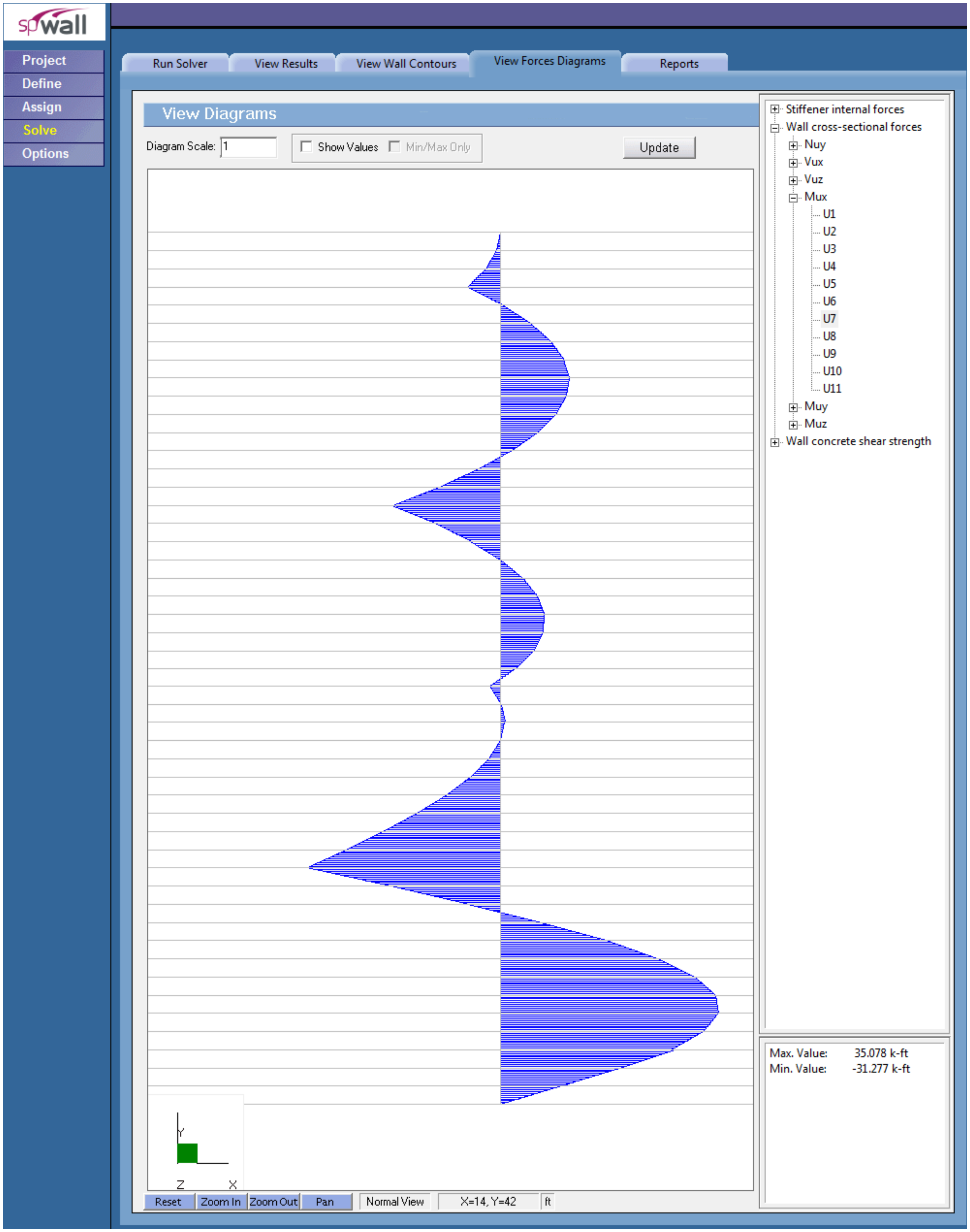


Figure 9 –Moment Diagram

5. Wall Displacement at Critical Section

```
Service combinations | Displacements | S4
==========================================

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

  Units:
  ======
  Displacement (Dx, Dy, Dz): in
```

Node	Dx	Dy	Dz
133	-3.11e-003	-5.89e-003	-2.57e-002
134	-2.99e-003	-5.68e-003	-2.63e-002
135	-2.82e-003	-5.46e-003	-2.72e-002
136	-3.94e-004	-4.78e-003	-2.40e-002
137	-2.63e-004	-4.75e-003	-2.28e-002
138	-1.44e-004	-4.75e-003	-2.21e-002
139	-4.52e-005	-4.75e-003	-2.17e-002
140	4.52e-005	-4.75e-003	-2.17e-002
141	1.44e-004	-4.75e-003	-2.21e-002
142	2.63e-004	-4.75e-003	-2.28e-002
143	3.94e-004	-4.78e-003	-2.40e-002
144	2.82e-003	-5.46e-003	-2.72e-002
145	2.99e-003	-5.68e-003	-2.63e-002
146	3.11e-003	-5.89e-003	-2.57e-002

$D_{z,avg}$ = 0.024 in.

Figure 10 –Displacement at Critical Section (Service Combinations)

```
Ultimate combinations | Displacements | U7
==========================================

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

  Units:
  ======
  Displacement (Dx, Dy, Dz): in
```

Node	Dx	Dy	Dz
133	-4.11e-003	-7.75e-003	-1.38e+000
134	-3.94e-003	-7.46e-003	-1.39e+000
135	-3.72e-003	-7.18e-003	-1.42e+000
136	-5.17e-004	-6.27e-003	-1.28e+000
137	-3.44e-004	-6.24e-003	-1.23e+000
138	-1.88e-004	-6.23e-003	-1.20e+000
139	-5.93e-005	-6.24e-003	-1.19e+000
140	5.93e-005	-6.24e-003	-1.19e+000
141	1.88e-004	-6.23e-003	-1.20e+000
142	3.44e-004	-6.24e-003	-1.23e+000
143	5.17e-004	-6.27e-003	-1.28e+000
144	3.72e-003	-7.18e-003	-1.42e+000
145	3.94e-003	-7.46e-003	-1.39e+000
146	4.11e-003	-7.75e-003	-1.38e+000

$D_{z,avg}$ = 1.299 in.

Figure 11 –Displacement at Critical Section (Ultimate Combinations)

6. Wall Cross-Sectional Forces at Critical Section

```
Ultimate combinations | Wall cross-sectional forces | U7
========================================================

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

  Units:
  ======
  Y-coordinate, X-centroid: ft
  Force (Vux, Nuy, Vuz): kips, Moment (Mux, Muy, Muz): k-ft

  Notes:
  ======
  (-) Horizontal cross-section below Y-coordinate
  (+) Horizontal cross-section above Y-coordinate

  ______Wall Cross-section______ ____________In-plane Forces___________ __________Out-of-plane Forces_________
  No.  Y-coordinate  X-centroid     Vux          Nuy          Muz          Vuz          Mux          Muy
  ---- ------------ ------------ ------------ ------------ ------------ ------------ ------------ ------------
    6-        2.000       12.500  7.3541e-013 -2.3495e+002  1.1384e-010 -9.9624e-001  3.5076e+001 -2.1383e-011
    6+        2.000       12.500  6.1118e-013 -2.3495e+002  3.8057e-011 -9.9624e-001  3.5078e+001  1.2709e-011
```

Figure 12 – Cross-Sectional Forces

7. Wall Reactions

```
Service combinations | Reactions | S4
======================================

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

  Units:
  ======
  Force (Fx, Fy, Fz): kips, Moment (Mx, My, Mz): k-ft

   Node      Fx           Fy           Fz           Mx           My           Mz
  ----- ------------ ------------ ------------ ------------ ------------ ------------
      1  8.8197e+000  2.1199e+001  1.2445e-001  9.4644e-016  3.3451e-016  1.6283e-015
      4 -9.0325e+000  2.1751e+001  1.7107e-001  5.7824e-016  3.1225e-016  7.4015e-017
      7  3.7975e+000  1.0611e+001  3.4124e-002 -2.0817e-015 -1.8504e-016  7.4015e-017
     10  7.8801e+000  2.8214e+001  1.9088e-001  8.0260e-016  4.0708e-016 -1.5728e-016
     13 -4.1452e+000  3.0799e+001  1.4921e-001 -1.0258e-015  6.4416e-016  6.6151e-016
     14  4.1452e+000  3.0799e+001  1.4921e-001 -5.2042e-015 -6.3838e-016  6.4763e-017
     17 -7.8801e+000  2.8214e+001  1.9088e-001 -2.1626e-016  7.6328e-016 -7.4015e-017
     20 -3.7975e+000  1.0611e+001  3.4124e-002 -9.5757e-016 -1.8735e-016  2.0354e-016
     23  9.0325e+000  2.1751e+001  1.7107e-001  2.5350e-015  1.2305e-015  2.2204e-016
     26 -8.8197e+000  2.1199e+001  1.2445e-001  2.2143e-015  5.1868e-016  3.7007e-016
    255  1.5533e-014 -6.5441e-014 -2.8704e-001 -2.3795e-016  1.6017e-016 -8.5487e-015
    256  3.0656e-014  4.6976e-015  1.1345e+000  2.6969e-015 -4.1633e-016  2.1002e-015
    257  7.8340e-014 -3.7727e-013  7.4090e-001 -6.4348e-016 -4.0246e-016  3.7204e-015
    258 -7.7716e-016 -2.1466e-013 -2.3198e-001 -9.4191e-016  6.7076e-017 -6.1340e-015
    259 -4.6407e-014  1.1893e-014  8.1933e-002  2.8575e-015 -1.1854e-017 -1.0200e-014
    260 -5.7288e-014  2.1710e-013  4.4531e-002 -1.6953e-015 -4.2244e-016 -6.5318e-015
    261  9.9920e-015  4.4853e-014  4.3485e-002  7.0754e-016  8.3194e-017 -2.8126e-015
  Sum of forces with respect to center of gravity (X, Y) = (12.50, 22.19) ft

   Sum       Fx           Fy           Fz           Mx           My           Mz
  ----- ------------ ------------ ------------ ------------ ------------ ------------
  Loads  0.0000e+000 -2.2515e+002 -2.3177e+001 -8.7705e+000 -6.2543e-015  7.3719e-014
  React -1.0430e-013  2.2515e+002  2.3177e+001  8.7704e+000 -1.7161e-012 -7.5558e-011
```

Figure 13 – Wall Reactions (Service Combinations)

Ultimate combinations | Reactions | U7
=======================================

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

Units:
======
Force (Fx, Fy, Fz): kips, Moment (Mx, My, Mz): k-ft

Node	Fx	Fy	Fz	Mx	My	Mz
1	1.1611e+001	2.7891e+001	2.2658e-001	-6.8788e-015	2.3916e-015	9.6219e-016
4	-1.1859e+001	2.8659e+001	1.7839e-001	7.7623e-015	-2.3500e-015	-3.3307e-016
7	4.9802e+000	1.4026e+001	-1.0948e-001	-2.5036e-014	-2.5258e-015	-1.1102e-016
10	1.0324e+001	3.7079e+001	3.8442e-001	-1.0145e-014	2.6645e-015	-5.1810e-016
13	-5.4455e+000	4.0435e+001	1.6738e-001	-8.6042e-016	-1.7532e-015	-7.8641e-016
14	5.4455e+000	4.0435e+001	1.6738e-001	-1.2212e-015	-3.1271e-015	8.3267e-017
17	-1.0324e+001	3.7079e+001	3.8442e-001	1.4849e-015	3.1641e-015	1.1472e-015
20	-4.9802e+000	1.4026e+001	-1.0948e-001	2.7210e-014	-1.5839e-014	-4.2559e-016
23	1.1859e+001	2.8659e+001	1.7839e-001	-1.3600e-015	-4.5334e-015	-4.4409e-016
26	-1.1611e+001	2.7891e+001	2.2658e-001	-2.4257e-016	-1.1010e-014	6.6613e-016
255	5.9813e-015	1.5099e-014	-1.1122e+000	1.8758e-015	-2.7015e-015	-9.5849e-015
256	1.3177e-014	-4.9658e-013	3.8552e+000	-9.8625e-015	-1.9984e-015	6.8926e-015
257	6.4206e-014	1.5932e-014	1.8703e+000	-1.4195e-014	-1.6653e-015	-7.6837e-015
258	-1.2990e-014	1.4766e-014	-9.0879e-001	-4.7350e-015	-3.8303e-015	2.1372e-015
259	-1.1768e-014	1.5637e-013	2.0181e-001	9.1041e-016	-6.1442e-016	1.4525e-015
260	-1.2168e-013	4.4775e-013	6.6647e-002	9.6743e-015	3.4791e-015	-2.4240e-015
261	5.7732e-015	2.8921e-013	6.7143e-002	-4.5109e-015	2.8999e-016	-7.7716e-016

Sum of forces with respect to center of gravity (X, Y) = (12.50, 22.19) ft

Sum	Fx	Fy	Fz	Mx	My	Mz
Loads	0.0000E+000	-2.9618E+002	-5.2976E+001	-2.5112E+001	-9.5294E-015	2.8829E-014
React	-1.2423E-013	2.9618E+002	5.2976E+001	2.5114E+001	3.4093E-011	-7.8326E-011

Figure 14 – Wall Reactions (Ultimate Combinations)

8. Wall Required Reinforcement

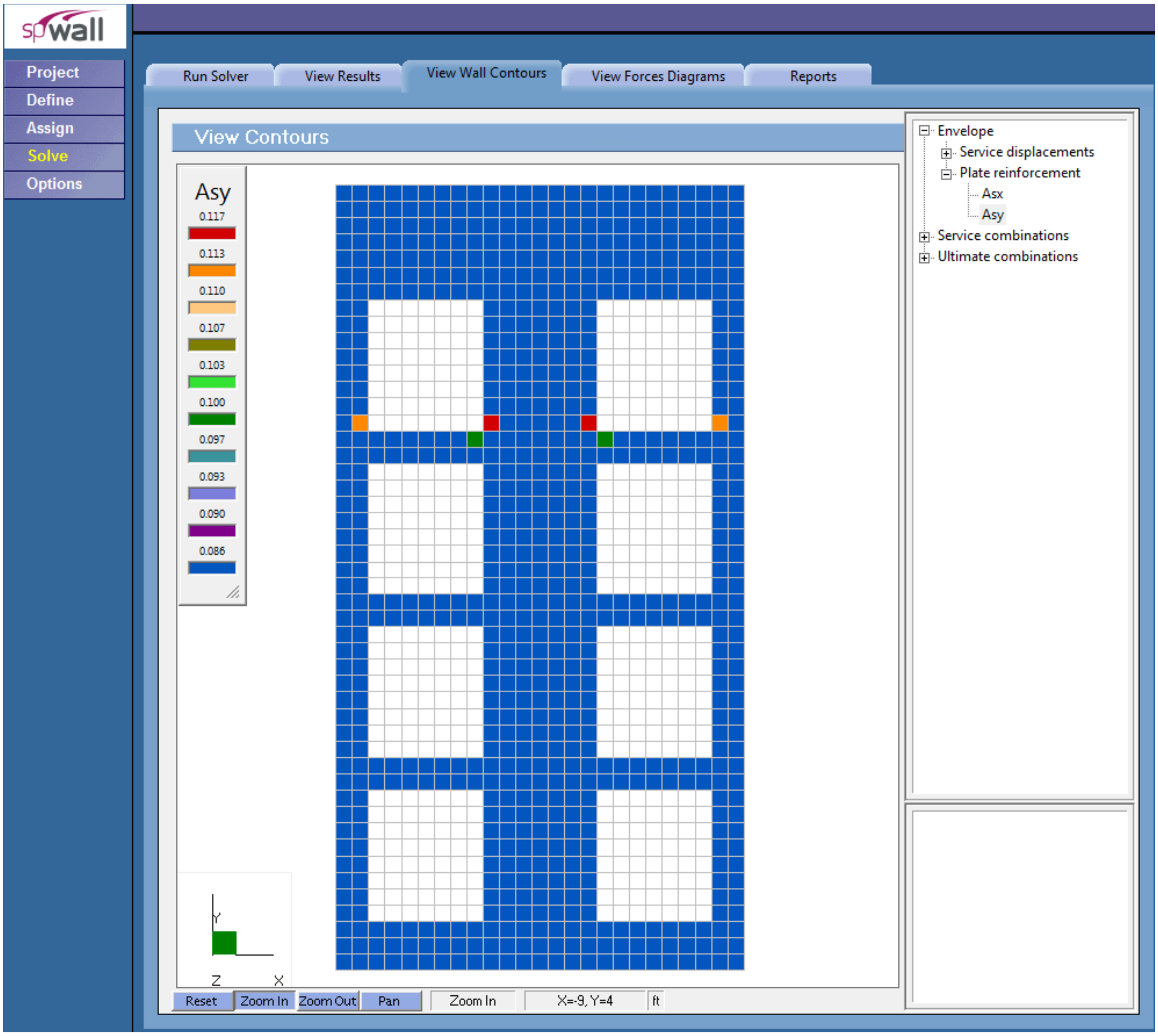


Figure 15 – Required Vertical Reinforcement
(Note: Only code minimum required reinforcement is required except for a few elements at the corner of third floor door openings)

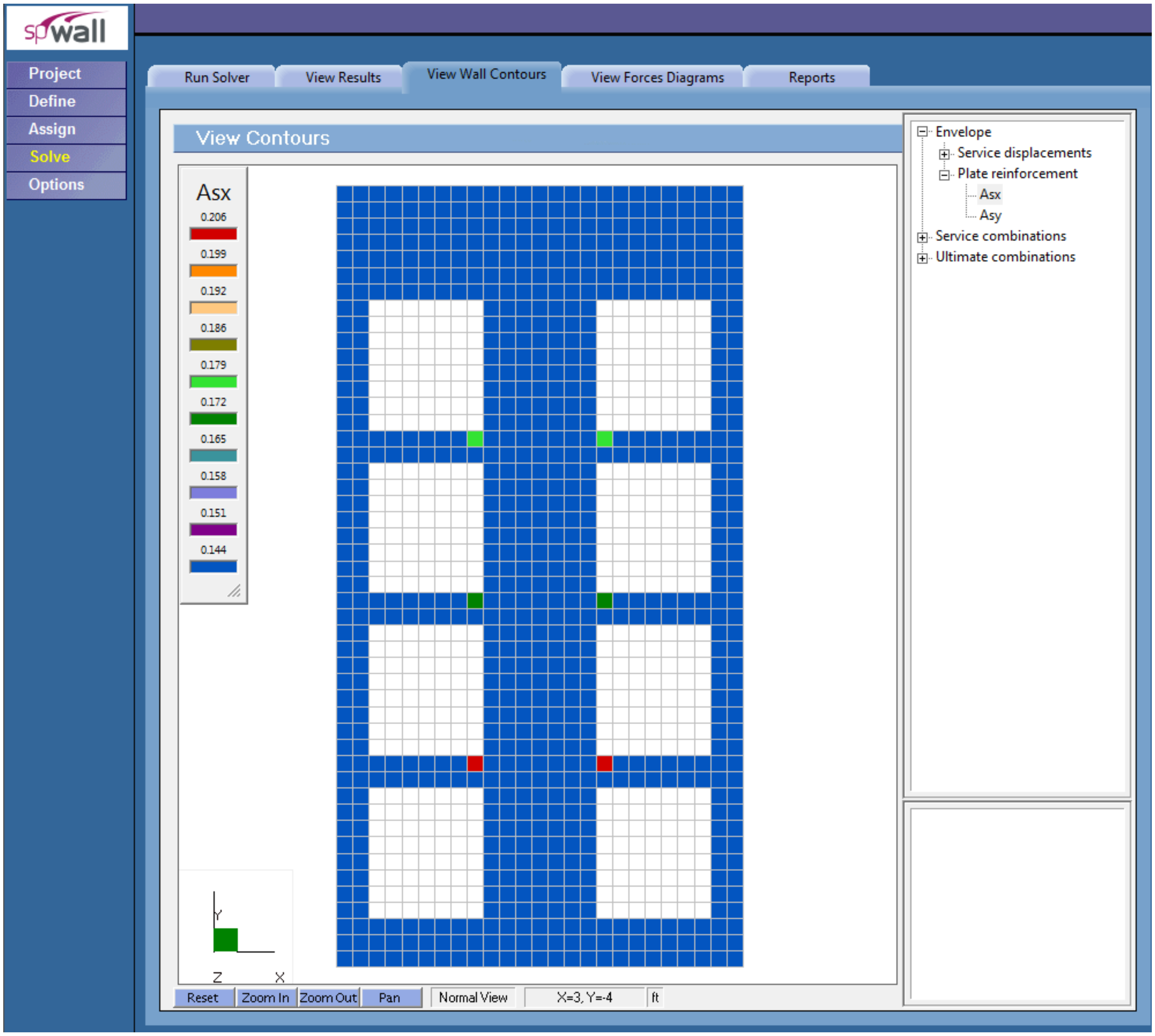


Figure 16 – Required Horizontal Reinforcement
(Note: Only code minimum required reinforcement is required except for a few elements at the corner of door openings)

9. Wall Interaction Diagram and Stability Check - spColumn

For the narrow wall piers an additional strength and stability check is performed to evaluate column behavior of the piers. The service axial loads and 1st order bending moments on the end piers at the first floor level are obtained from spWall model. The effective length factor "k" is calculated using ACI 318-14 provisions in section 6.2 assuming the wall is pinned at the bottom and fixed at the top in a nonsway frame can be estimated and taken as 0.63.

Note that according to ACI 318-14 chapter 10, for "columns" with cross sections larger than required by considerations of loading, it shall be permitted to base gross area considered, required reinforcement, and design strength on a reduced effective area, not less than one-half the total area. More information about this topic can be found in "Columns with Low Reinforcement – Architectural Columns" technical article in StructurePoint Resources page. In this model the "Structural" class is used for the wall pier.

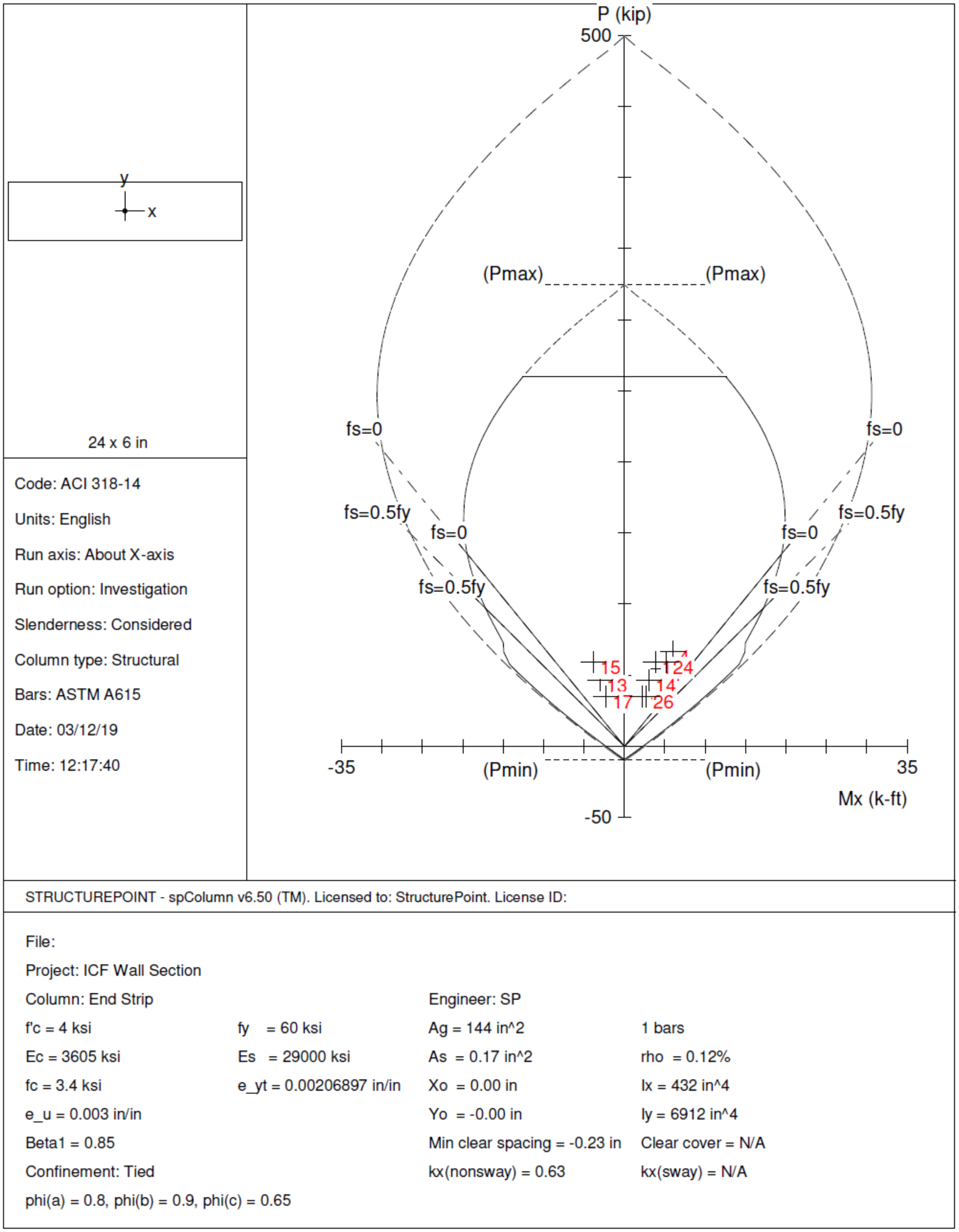


Figure 17 – Wall Right Leg (Pier) Interaction Diagram

Load Combo			1st Order M_{ns} k-ft	M_s k-ft	M_u k-ft	M_{min} k-ft	2nd Order	M_i k-ft	M_c k-ft	Ratio 2nd/1st
1	U1	Top	0.00	(N/A)	0.00	3.53	M_1=	0.00	4.82	1.368
1	U1	Bot	0.00	(N/A)	0.00	3.53	M_2=	0.00	4.82	1.368
1	U2	Top	0.00	(N/A)	0.00	4.32	M_1=	0.00	6.00	1.389
1	U2	Bot	0.00	(N/A)	0.00	4.32	M_2=	0.00	6.00	1.389
1	U3	Top	0.00	(N/A)	0.00	3.84	M_1=	0.00	5.19	1.354
1	U3	Bot	0.00	(N/A)	0.00	3.84	M_2=	0.00	5.19	1.354
1	U4	Top	0.00	(N/A)	1.10	3.02	M_2=	1.10	3.02	1.000
1	U4	Bot	0.00	(N/A)	0.00	3.02	M_1=	0.00	3.02	1.000
1	U5	Top	0.00	(N/A)	1.37	3.84	M_2=	1.37	3.84	1.000
1	U5	Bot	0.00	(N/A)	0.00	3.84	M_1=	0.00	3.84	1.000
1	U6	Top	0.00	(N/A)	1.37	2.27	M_2=	1.37	2.27	1.000
1	U6	Bot	0.00	(N/A)	0.00	2.27	M_1=	0.00	2.27	1.000
1	U7	Top	0.00	(N/A)	-1.10	-3.02	M_2=	-1.10	[illegible]	1.000
1	U7	Bot	0.00	(N/A)	0.00	3.02	M_1=	0.00		1.000
1	U8	Top	0.00	(N/A)	-1.37	-3.84	M_2=	-1.37	-3.84	1.000
1	U8	Bot	0.00	(N/A)	0.00	3.84	M_1=	0.00	3.84	1.000
1	U9	Top	0.00	(N/A)	-1.37	-2.27	M_2=	-1.37	-2.27	1.000
1	U9	Bot	0.00	(N/A)	0.00	2.27	M_1=	0.00	2.27	1.000
1	U10	Top	0.00	(N/A)	0.00	3.84	M_1=	0.00	5.19	1.354
1	U10	Bot	0.00	(N/A)	0.00	3.84	M_2=	0.00	5.19	1.354
1	U11	Top	0.00	(N/A)	0.00	2.27	M_1=	0.00	2.74	1.209
1	U11	Bot	0.00	(N/A)	0.00	2.27	M_2=	0.00	2.74	1.209
1	U12	Top	0.00	(N/A)	0.00	3.84	M_1=	0.00	5.19	1.354
1	U12	Bot	0.00	(N/A)	0.00	3.84	M_2=	0.00	5.19	1.354
1	U13	Top	0.00	(N/A)	0.00	2.27	M_1=	0.00	2.74	1.209
1	U13	Bot	0.00	(N/A)	0.00	2.27	M_2=	0.00	2.74	1.209

< 1.400

Figure 18 – Wall End Pier Stability Check (ACI 318-14 (6.2.6))

No.	Load Combo			Demand P_u kip	M_{ux} k-ft	Capacity ϕP_n kip	ϕM_{nx} k-ft	Parameters at Capacity NA Depth in	ε_t	ϕ	Capacity Ratio
1	1	U1	Top	54.25	4.82	15.51	5.85	0.40	0.01962	0.900	0.84
2	1	U1	Bot	54.25	4.82	15.51	5.85	0.40	0.01962	0.900	0.84
3	1	U2	Top	66.50	6.00	21.83	7.23	0.50	0.01503	0.900	0.82
4	1	U2	Bot	66.50	6.00	21.83	7.23	0.50	0.01503	0.900	0.82
5	1	U3	Top	59.00	5.19	17.51	6.30	0.43	0.01793	0.900	0.83
6	1	U3	Bot	59.00	5.19	17.51	6.30	0.43	0.01793	0.900	0.83
7	1	U4	Top	46.50	3.02	7.43	4.03	0.27	0.03053	0.900	0.84
8	1	U4	Bot	46.50	3.02	7.43	4.03	0.27	0.03053	0.900	0.84
9	1	U5	Top	59.00	3.84	11.89	5.05	0.34	0.02347	0.900	0.81
10	1	U5	Bot	59.00	3.84	11.89	5.05	0.34	0.02347	0.900	0.81
11	1	U6	Top	34.88	2.27	3.27	3.05	0.20	0.04159	0.900	0.87
12	1	U6	Bot	34.88	2.27	3.27	3.05	0.20	0.04159	0.900	0.87
13	1	U7	Top	46.50	-3.02	7.43	-4.03	0.27	0.03053	0.900	0.84
14	1	U7	Bot	46.50	3.02	7.43	4.03	0.27	0.03053	0.900	0.84
15	1	U8	Top	59.00	-3.84	11.89	-5.05	0.34	0.02347	0.900	0.81
16	1	U8	Bot	59.00	3.84	11.89	5.05	0.34	0.02347	0.900	0.81
17	1	U9	Top	34.88	-2.27	3.27	-3.05	0.20	0.04159	0.900	0.87
18	1	U9	Bot	34.88	2.27	3.27	3.05	0.20	0.04159	0.900	0.87
19	1	U10	Top	59.00	5.19	17.51	6.30	0.43	0.01793	0.900	0.83
20	1	U10	Bot	59.00	5.19	17.51	6.30	0.43	0.01793	0.900	0.83
21	1	U11	Top	34.88	2.74	5.09	3.48	0.23	0.03596	0.900	0.88
22	1	U11	Bot	34.88	2.74	5.09	3.48	0.23	0.03596	0.900	0.88
23	1	U12	Top	59.00	5.19	17.51	6.30	0.43	0.01793	0.900	0.83
24	1	U12	Bot	59.00	5.19	17.51	6.30	0.43	0.01793	0.900	0.83
25	1	U13	Top	34.88	2.74	5.09	3.48	0.23	0.03596	0.900	0.88
26	1	U13	Bot	34.88	2.74	5.09	3.48	0.23	0.03596	0.900	0.88

Figure 19 – Wall End Pier Strength Check

10. ICF Wall Analysis– Alternative Analysis Method

ICF walls can be analyzed using the provisions of Chapter 11 of the ACI 318. Most walls, and especially slender walls, are widely evaluated using the "Alternative Method for Out-of-Plane Slender Wall Analysis" in Section 11.8. The requirements of this procedure are summarized below:

- The cross section shall be constant over the height of the wall **ACI 318-14 (11.8.1.1(a))**
- The wall can be designed as simply supported **ACI 318-14 (11.8.2.1)**
- Maximum moments and deflections occurring at midspan **ACI 318-14 (11.8.2.1)**
- The wall must be axially loaded **ACI 318-14 (11.8.2.1)**
- The wall must be subjected to an out-of-plane uniform lateral load **ACI 318-14 (11.8.2.1)**
- The wall shall be tension-controlled **ACI 318-14 (11.8.1.1(b))**
- The reinforcement shall provide design strength greater than cracking strength **ACI 318-14 (11.8.1.1(c))**
- P_u at the midheight section does not exceed 0.06 $f_c'A_g$ **ACI 318-14 (11.8.1.1(d))**
- Out-of-plane deflection due to service loads including $P\Delta$ effects does not exceed $l_c/150$ **ACI 318-14 (11.8.1.1(c))**

The ICF wall under study is analyzed using this method, the results obtained from the analysis are summarized below considering minimum reinforcement being used (0.12%). More details about the use of this method can be found in "Precast Concrete Bearing Wall Panel Design" example.

$$M_u = \frac{M_{ua}}{1 - \dfrac{5 \times P_u \times l_c^2}{0.75 \times 48 \times E_c \times I_{cr}}} = 4.1 \text{ kip-ft}$$ **ACI 318-14 (11.8.3.1d)**

$$M_{cr} = \frac{f_r I_g}{y_t} = 5.7 \text{ kip-ft}$$ **ACI 318-14 (24.2.3.5b)**

$$\phi M_n = 12.1 \text{ kip-ft} > M_u = 4.1 \text{ kip-ft} \ (\textbf{o.k.})$$ **ACI 318-14 (11.5.1.1(b))**

$$\phi M_n = 12.1 \text{ kip-ft} > M_{cr} = 5.7 \text{ kip-ft} \ (\textbf{o.k.})$$ **ACI 318-14 (11.8.1.1(c))**

Note that the wall vertical stress check shows that the wall is stressed in compression beyond the 6% limit and the use of the alternative analysis method might not be suitable as follows:

$$\frac{P_u}{A_g} = 356 \text{ psi} > 0.06 \times f_c' = 240 \text{ psi} \ (\textbf{N.G.})$$ **ACI 318-14 (11.8.1.1(d))**

The maximum out-of-plane deflection (Δ_s) due to service lateral and eccentric vertical loads, including PΔ effects, shall not exceed $l_c/150$. **ACI 318-14 (11.8.1.1(e))**

$$\Delta_s = 0.009 \text{ in.} < \frac{l_c}{150} = 0.800 \text{ in.} \quad (\textbf{o.k.})$$

11. Conclusions and Observations

Based on the output of spWall, spColumn, and alternative analysis method results indicate the end piers are optimally designed leaving very little margin in the strength and stability checks.

It is recommended to further refine loads and boundary conditions or increase the pier section dimensions if higher safety margins are desired. For instance relocating the doors to achieve a 3 ft pier and possibly increasing the thickness to 8 in. may be advisable for the first level.