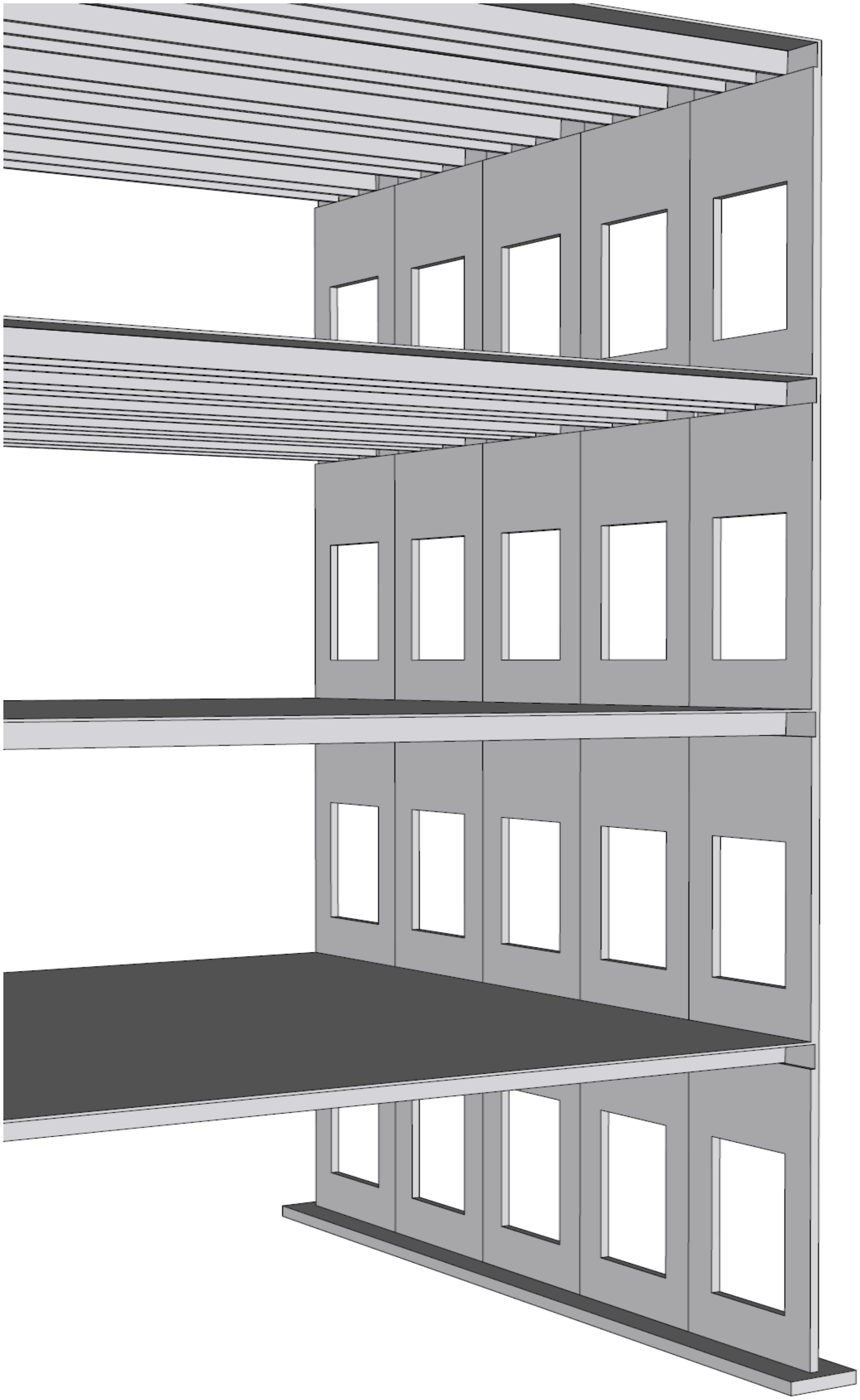
Multi-Story Tilt-Up Wall Panel with Openings Analysis and Design (ACI 318-14 – ACI 551)



Reinforced Concrete Multi-Story Tilt-Up Wall Panel with Openings Analysis and Design (ACI 318-14 – ACI 551)

Tilt-up is form of construction with increasing popularity owing to its flexibility and economics. Tilt-up concrete is essentially a precast concrete that is site cast instead of traditional factory cast concrete members. A structural reinforced concrete multi-story tilt-up wall panel with openings in a building provides gravity and lateral load resistance for the applied loads from roof and floor joists.

The existing tilt-up wall panel in the following figure will be investigated to evaluate the as-built design to resist the applied gravity and lateral loads. The results, from ACI 318 procedure, will then be compared with numerical finite element analysis results obtained from spWall engineering software program from StructurePoint. Additionally, different modeling and analysis techniques using spWall software to investigate and design multi-story tilt-up wall panels with openings are discussed.

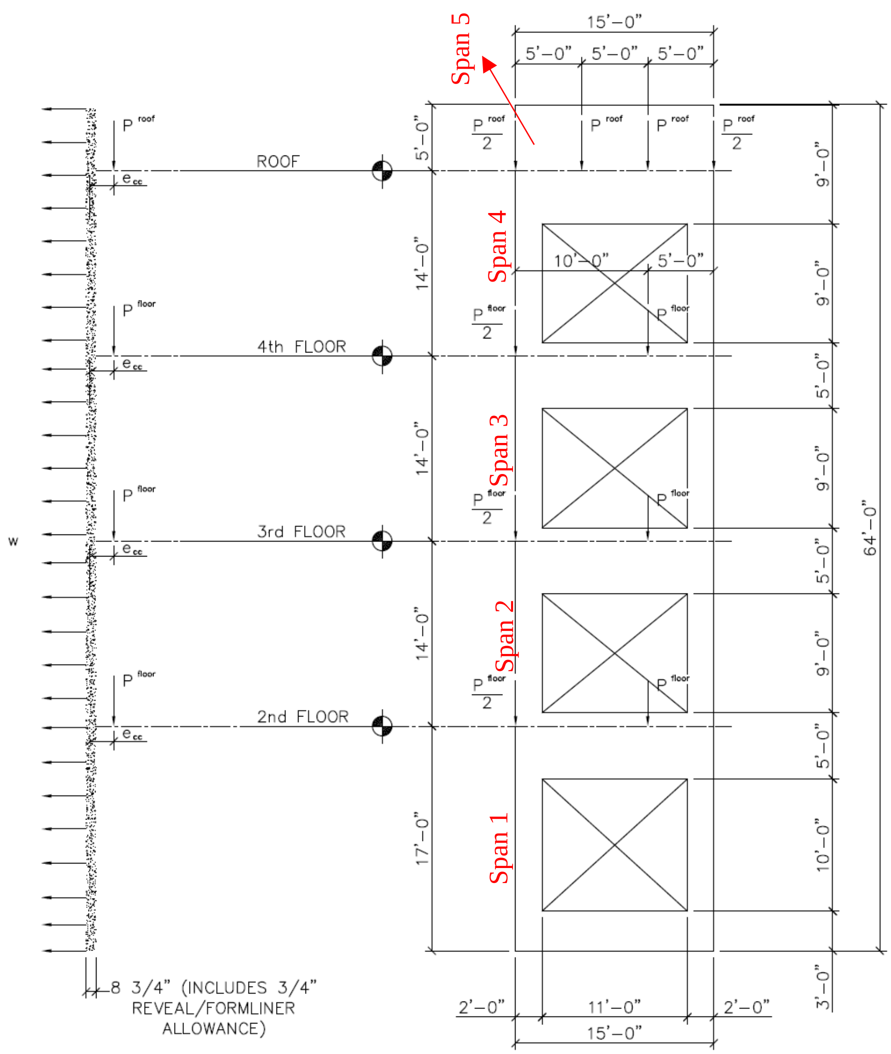


Figure 1 – Reinforced Concrete Multi-Story Tilt-Up Wall Panel Geometry

Contents

Code

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

Reference

- Design Guide for Tilt-Up Concrete Panels, ACI 551.2R-15, 2015
- spWall Engineering Software Program Manual v10.00, STRUCTUREPOINT, 2022

Design Data

f_c' = 4,000 psi normal weight concrete (w_c = 150 pcf)

f_y = 60,000 psi

As-built wall thickness = 8.75 in.

Load eccentricity = e_{cc} = 6.75 in.

As-built vertical reinforcement: 4 #5 per layer (double layer) for the left leg (design strip)

4 #5 per layer (double layer) for the right leg (design strip)

1. Method of Solution

1.1. Background

According to ACI 551, continuous wall panels maybe analyzed and designed using the alternative design method in Chapter 14 of ACI 318-11 (Alternative Method for Out-of-Plane Slender Wall Analysis in Chapter 11 of ACI 318-14). The effect of openings on out-of-plane bending in tilt-up panels can be approximated in hand calculations by a simplified, one-dimensional strip analysis. Where openings occur, the entire lateral and axial load, including self-weight above the critical section, is distributed to supporting legs or design strips at each side of the opening (sometimes referred to as wall piers). ***ACI 551.2R-15 (7.2)***

The effective width of the strip should be limited to approximately 12 times the panel thickness to avoid localized stress concentrations along the edge of the opening. This limit is not mandated by ACI 318, but is included as a practical guideline where the opening width is less than one-half the clear vertical span. In most cases the tributary width for loads can be taken as the width of the strip plus one-half the width of adjacent openings. Tilt-up design strips should have constant properties for the full height and the reinforcement should not be cut off just above or below the opening. Thickened vertical or horizontal sections can be introduced within the panel where openings are large or where there are deep recesses on the exterior face. Some conditions may require ties around all vertical reinforcement bars in a vertical pilaster (wall pier) for the full height of the tilt-up panel. ***ACI 551.2R-15 (7.2)***

No minimum limits are provided in ACI 551 on the width or thickness of the wall piers in panels with openings. Similarly, no limits are provided on horizontal sections (header beams) where openings are large. Therefore, slenderness effects and reinforcement size and confinement must be optimized to achieve adequate strength and stability. Slender column and deep beam provisions of ACI 318 can quickly become applicable in such circumstances. A detailed investigation of slenderness effects on the stability of the design strips is provided at the end of this example.

1.2. Tilt-Up Wall Panel Design Strips

Using ACI 551 guidance, the wall panel can be idealized as two design strips with constant section as shown. The left strip analysis and design will be carried out in details.

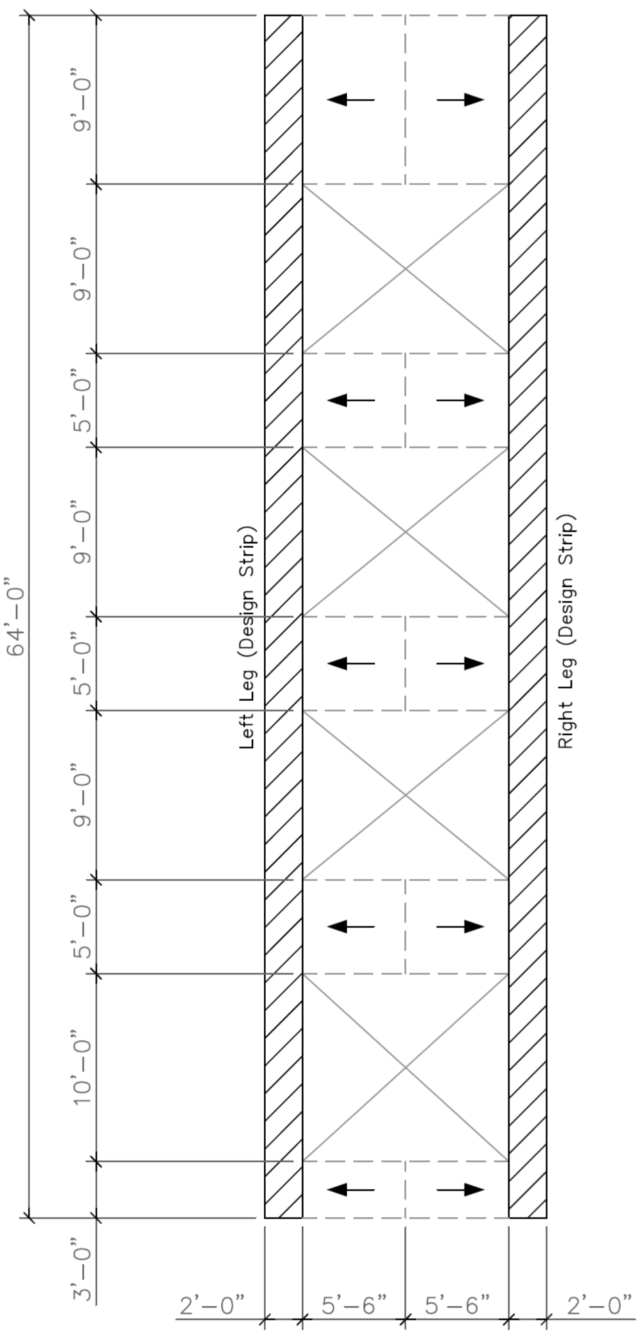


Figure 2 – Tilt-Up Design Strips Tributary Widths – Self-weight & Wind Loads

2. Tilt-Up Wall Structural Analysis

2.1. Loads and Load Combinations

Roof dead load (P_{DL}^{roof}) = 2.5 kip

Roof live load (P_{LL}^{roof}) = 2.0 kip

Floor dead load (P_{DL}^{floor}) = 17.6 kip

Floor live load (P_{LL}^{floor}) = 10.0 kip

Wind load = 27.2 psf (out of plane)

= 0.00 psf (in plane)

The tributary width for loads can be taken as the width of the strip plus one-half the width of adjacent openings. Joists loads at each floor level including the roof are divided between the individual strips assuming an equivalent simply supported beams with the supports at the centerline of each strip.

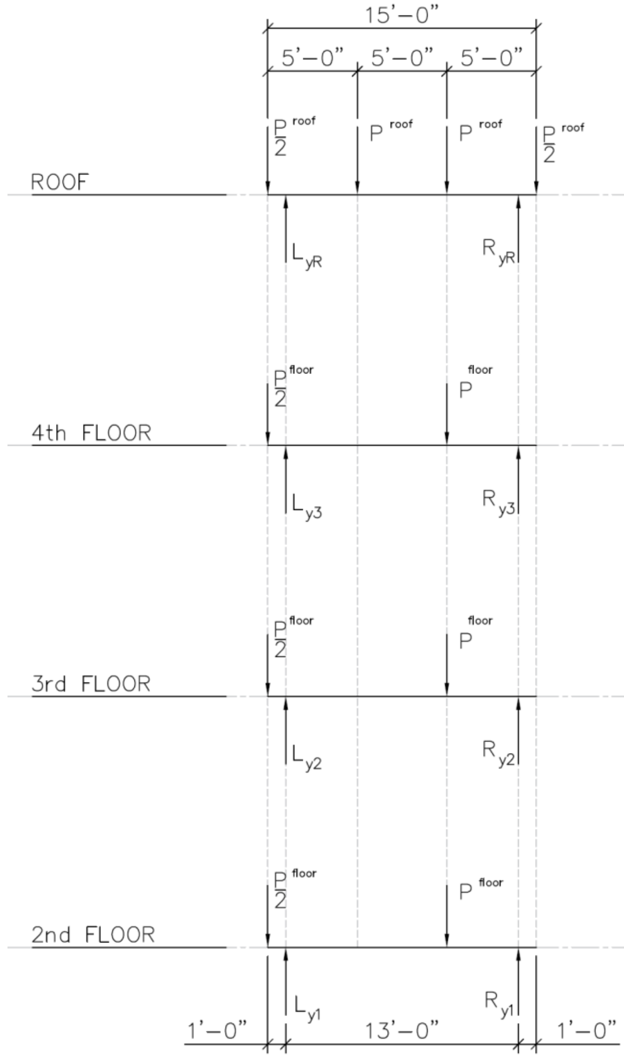


Figure 3 – Tilt-Up Design Strips Tributary Widths – Dead & Live Loads

Table 1 - Joists Loads at Each Floor Level				
Floor Level	Left Strip (L_y)		Right Strip (R_y)	
	P_{DL}, kip	P_{LL}, kip	P_{DL}, kip	P_{LL}, kip
First	14.89	8.46	11.51	6.54
Second	14.89	8.46	11.51	6.54
Third	14.89	8.46	11.51	6.54
Roof	3.75	3.00	3.75	3.00

For maximum positive 1st order moment section (43 ft):

$$\text{Wall self-weight} = \frac{8.75}{12}\times 150\times\left[2\times(5+14+2)+\frac{11}{2}\times(5+14+2-9)\right]\times\frac{1\text{ kip}}{1000\text{ lb}} = 11.81\text{ kip}$$

For maximum negative 1st order moment section (17ft):

$$\text{Wall self-weight} = \frac{8.75}{12}\times 150\times\left[2\times(64-17)+\frac{11}{2}\times(64-17-3\times 9)\right]\times\frac{1\text{ kip}}{1000\text{ lb}} = 22.31\text{ kip}$$

Self-weight is calculated at the critical sections based on the 1st order moment diagram shown in the next section.

The load combination considered for structural analysis and design is 1.2D + 0.5Lr + 1.0L + 1.0W.

2.2. Wall First Order Structural Analysis

Using the loads and load combination calculated in the previous section, the moment diagram of 1st order moment can be obtained as shown in the following figure using the method illustrated later in this example.

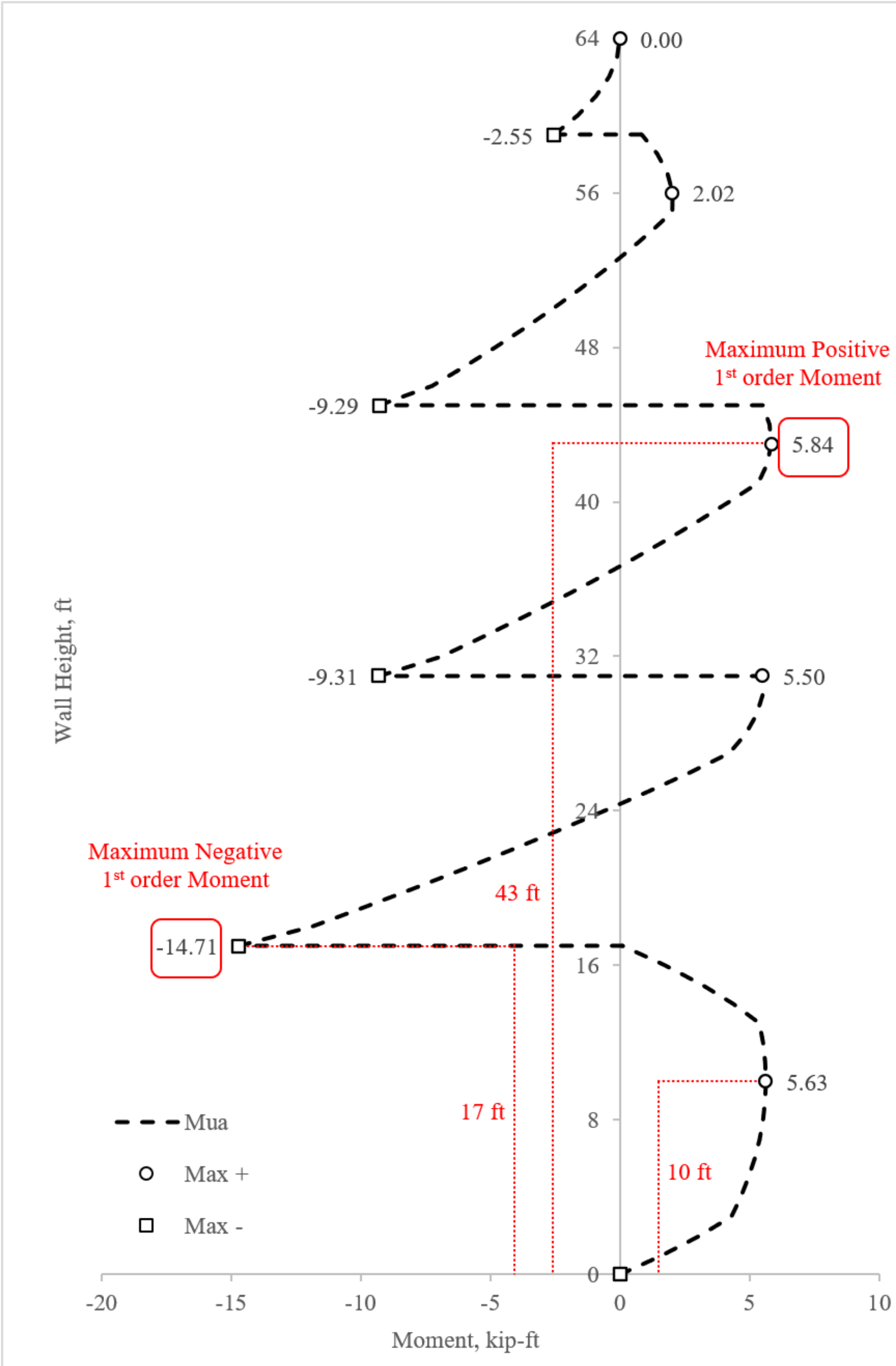


Figure 4 – 1st Order Moment Diagram for Left Strip

2.3. Wall Second Order Structural Analysis

For maximum positive 1st order moment section (43 ft):

The maximum factored wall forces including moment magnification due to second order (P-Δ) effects can be calculated as follows:

$$P_{um} = 1.2\times(3.75+14.89+11.80)+0.5\times3.00+1.0\times8.46 = 46.51\text{ kip}$$

Calculate the effective area of longitudinal reinforcement in a slender wall for obtaining an approximate cracked moment of inertia.

$$A_{se} = A_s + \frac{P_{um}\times h}{2\times f_y\times d} = 1.24+\frac{46.51\times8.75}{2\times60\times(8.75-1.69)} = 1.72\text{ in.}^2$$ ***ACI 318-14 (R11.8.3.1)***

The following calculation are performed with the effective area of steel in lieu of the actual area of steel.

$$a = \frac{A_{se}\times f_y}{0.85\times f'_c\times b} = \frac{1.72\times60}{0.85\times4\times(2\times12)} = 1.265\text{ in.}$$

$$c = \frac{a}{\beta_1} = \frac{1.265}{0.85} = 1.488\text{ in.}$$

$$\frac{c}{d} = \frac{1.488}{8.75-1.69} = 0.211 < 0.375 \therefore \text{ tension-controlled}$$ ***ACI 318-14 (R21.2.2)***

$$\phi = 0.9$$ ***ACI 318-14 (Table 21.2.2)***

$$I_{cr} = n\times A_{se}\times(d-c)^2+\frac{l_w\times c^3}{3}$$ ***ACI 318-14 (11.8.3.1(c))***

$$E_c = 57,000\times\sqrt{f'_c} = 57,000\times\sqrt{4,000} = 3,605,000\text{ psi}$$ ***ACI 318-14 (19.2.2.1(b))***

$$n = \frac{E_s}{E_c} = \frac{29,000}{3,605} = 8.0 > 6.0\ (\textbf{o.k.})$$ ***ACI 318-14 (11.8.3.1)***

$$I_{cr} = 8.0\times1.72\times(7.06-1.488)^2+\frac{(2\times12)\times1.488^3}{3} = 456.00\text{ in.}^4$$ ***ACI 318-14 (11.8.3.1(c))***

$$M_u = \frac{M_{ua}}{1-\dfrac{P_{um}}{0.75\times K_b}}$$ ***ACI 318-14 (Eq. 11.8.3.1(d))***

Where M_{ua} is the maximum factored moment along the wall due to lateral and eccentric vertical loads, not including PΔ (second order) effects. This value can be seen in the previous figure. ***ACI 318-14 (11.8.3.1)***

$$K_b = \frac{48 \times E_c \times I_{cr}}{5 \times l_c^2} = \frac{48 \times 3605 \times 456.00}{5 \times (14 \times 12)^2} = 559.15 \text{ kip}$$

$$M_u = \frac{5.84}{1 - \dfrac{46.51}{0.75 \times 559.15}} = 6.57 \text{ ft-kip}$$

2.4. Tension-controlled verification **_ACI 318-14 (11.8.1.1(b))_**

$$P_n = \frac{P_{um}}{\phi} = \frac{46.51}{0.9} = 51.67 \text{ kips}$$

$$a = \frac{A_{se,w} \times f_y}{0.85 \times f_c' \times l_w} = \frac{\dfrac{P_n \times h}{2 \times d} + A_s \times f_y}{0.85 \times f_c' \times l_w} = \frac{\dfrac{51.67 \times 8.75}{2 \times 7.06} + 1.24 \times 60}{0.85 \times 4 \times 2 \times 12} = 1.304 \text{ in.}$$

$$c = \frac{a}{\beta_1} = \frac{1.304}{0.85} = 1.534 \text{ in.}$$

$$\varepsilon_t = \left(\frac{0.003}{c}\right) \times d_t - 0.003 = \left(\frac{0.003}{1.534}\right) \times 7.06 - 0.003 = 0.0108 > 0.005$$

Therefore, section is tension controlled **_ACI 318-14 (Table 21.2.2)_**

3. Tilt-Up Wall Flexural Strength

3.1. Wall Cracking Moment Capacity (M_{cr})

Determine f_r = Modulus of rapture of concrete and I_g = Moment of inertia of the gross uncracked concrete section to calculate M_{cr}

$$f_r = 7.5\lambda\sqrt{f_c'} = 7.5 \times 1.0 \times \sqrt{4,000} = 474.32 \text{ psi}$$ **_ACI 318-14 (19.2.3.1)_**

$$I_g = \frac{l_w h^3}{12} = \frac{(2 \times 12) \times 8.75^3}{12} = 1339.84 \text{ in.}^4$$

$$y_t = \frac{h}{2} = \frac{8.75}{2} = 4.38 \text{ in.}$$

$$M_{cr} = \frac{f_r I_g}{y_t} = \frac{474.32 \times 1339.84}{4.38} \times \frac{1}{1000} \times \frac{1}{12} = 12.11 \text{ ft-kip}$$ **_ACI 318-14 (24.2.3.5(b))_**

3.2. Wall Flexural Moment Capacity (ϕM_n)

$$M_n = A_{se} \times f_y \times \left(d - \frac{a}{2} \right) = 1.72 \times 60 \times \left(7.06 - \frac{1.265}{2} \right) = 55.29 \text{ ft-kip}$$

It was shown previously that the section is tension controlled → ϕ = 0.9

$$\phi M_n = \phi \times M_n = 0.9 \times 55.29 = 49.76 \text{ ft-kip} > M_u = 6.57 \text{ ft-kip} \ (\textbf{o.k.})$$ ***ACI 318-14 (11.5.1.1(b))***

$$\phi M_n = 49.76 \text{ ft-kip} > M_{cr} = 12.11 \text{ ft-kip} \ (\textbf{o.k.})$$ ***ACI 318-14 (11.8.1.1(c))***

$$\Delta_u = \frac{M_u}{0.75 \times K_b} = \frac{6.57 \times 12}{0.75 \times 559.15} = 0.188 \text{ in.}$$ ***ACI 318-14 (11.8.3.1(b))***

The same procedure was repeated for positive moment section at 8 ft height and negative moment section at 17 ft height (see the following table).

Table 2 –Multi-Story Panel Hand Solution Results at Critical Sections (Left Strip)				
Location	M_{ua} (kip-ft)	M_u (kip-ft)	Magnifier	$D_{z,ultimate}$ (in.)
y = 8 ft (Span 1)	+5.63	+7.15	1.271	0.284
y = 43 ft (Span 3)	+5.84	+6.57	1.125	0.188
y = 17 ft (Span 2)	-14.71	-17.94	1.220	0.000

3.3. Tilt-Up Wall Flexural Reinforcement

At the maximum positive moment location in span 3, I_{cr} equals 456.00 in.^{4} corresponding to 4 #5 bars. At this location, the wall capacity far exceeds the maximum moment (ϕM_n = 49.76 ft-kip >> M_u = 6.57 ft-kip), the corresponding cracking coefficient ($0.75I_{cr}/I_g$) = 0.25525. If this is used in a FEA like spWall, the resulting design flexural reinforcement will be far less than provided in this example. While this example uses a conservative As, a lower value may be possibly obtained for strength calculations by the optimization procedure as illustrated in section 13 of "Reinforced Concrete Tilt-Up Wall Panel with Opening Analysis and Design (ACI 318-14 – ACI 551)" example in StructurePoint's Design Examples Library.

4. Tilt-Up Wall Vertical Strength Check

$$\frac{P_{um}}{A_g} = \frac{46.51 \times 1000}{8.75 \times (2 \times 12)} = 221.46 \text{ psi} < 0.06 \times f'_c = 0.06 \times 4{,}000 = 240 \text{ psi} \ (\textbf{o.k.})$$ ***ACI 318-14 (11.8.1.1(d))***

5. Tilt-Up Wall Shear Strength Check

In-plane shear is not evaluated since in-plane shear forces are not applied in this example. Out-of-plane shear due to lateral load should be checked against the shear capacity of the wall. By inspection of the maximum second order shear forces, it can be determined that the maximum shear force is under 3 kips. The wall has a shear capacity approximately 26.5 kips and no detailed calculations are required by engineering judgement. (See figure 15 for detailed shear force diagram).

Repeating the same process for the right leg (design strip) leads to the following results:

Table 3 –Multi-Story Panel Hand Solution Results at Critical Sections (Right Strip)

Location	M_{ua} (kip-ft)	M_u (kip-ft)	Magnifier	$D_{z,ultimate}$ (in.)
y = 8 ft (Span 1)	+5.06	+6.30	1.245	0.255
y = 43 ft (Span 3)	+4.27	+4.74	1.110	0.139
y = 17 ft (Span 2)	-12.38	-14.74	1.191	0.000

6. Tilt-Up Wall Panel Design Strip Analysis – spWall Software

spWall is a program for the analysis and design of reinforced concrete shear walls, tilt-up walls, precast walls 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 any 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 considers 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 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 reinforced concrete wall in this example. No in-plane forces were specified for this model.

In this example, ultimate load combination #1 is used in conjunction with one service load combination to report service and ultimate level displacements

Ultimate load combination #1: $1.2D + 0.5L_r + 1.0L + 1.0W$

Service load combination #1: $1.0D + 0.5L + 0.5W$

Special loading provisions are made to incorporate the self-weight and wind pressure from windows into the model. Care must be used in determining proper load application points based on windows and door anchorage to the wall. No in-plane lateral forces were specified for this model.

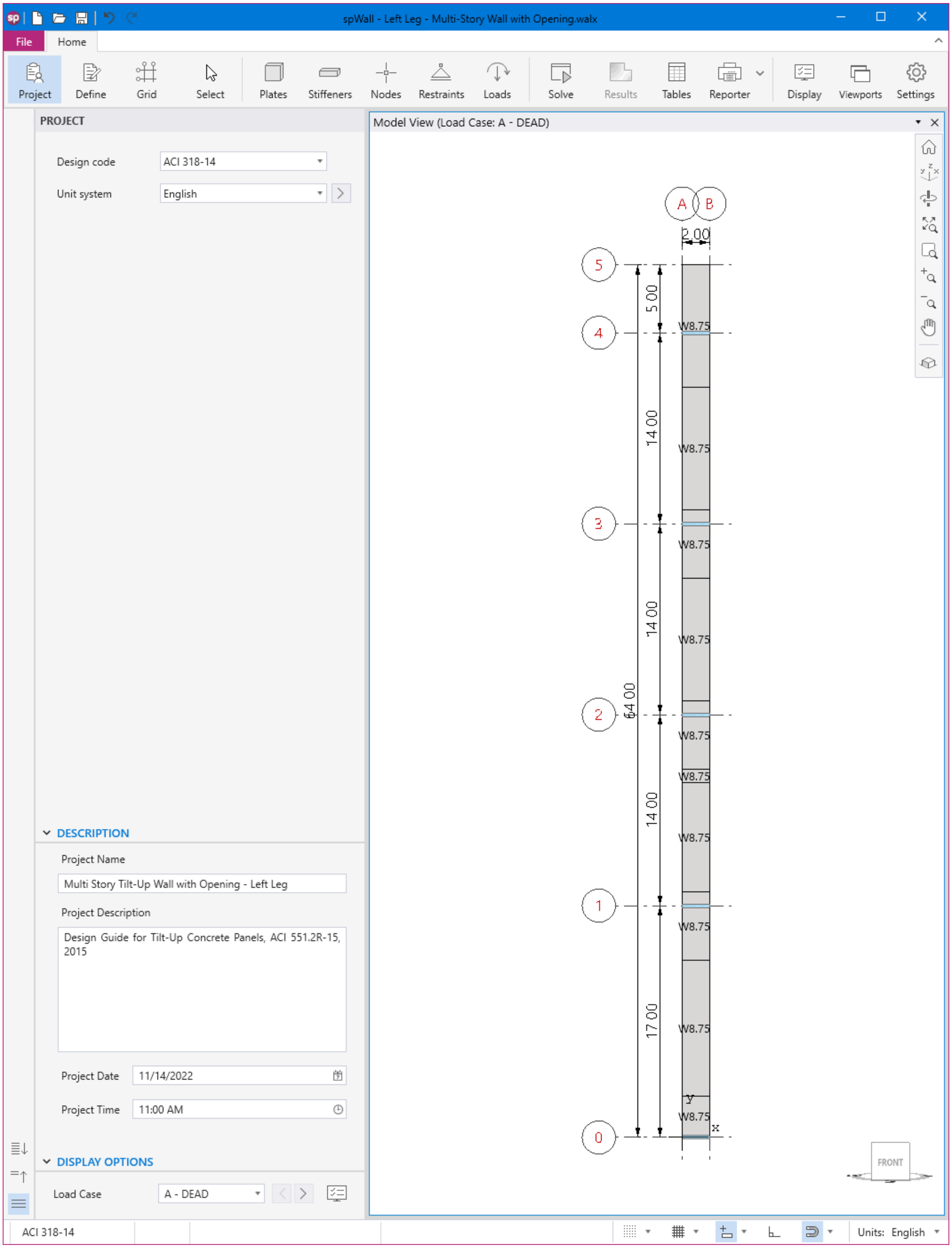


Figure 5 – spWall Interface

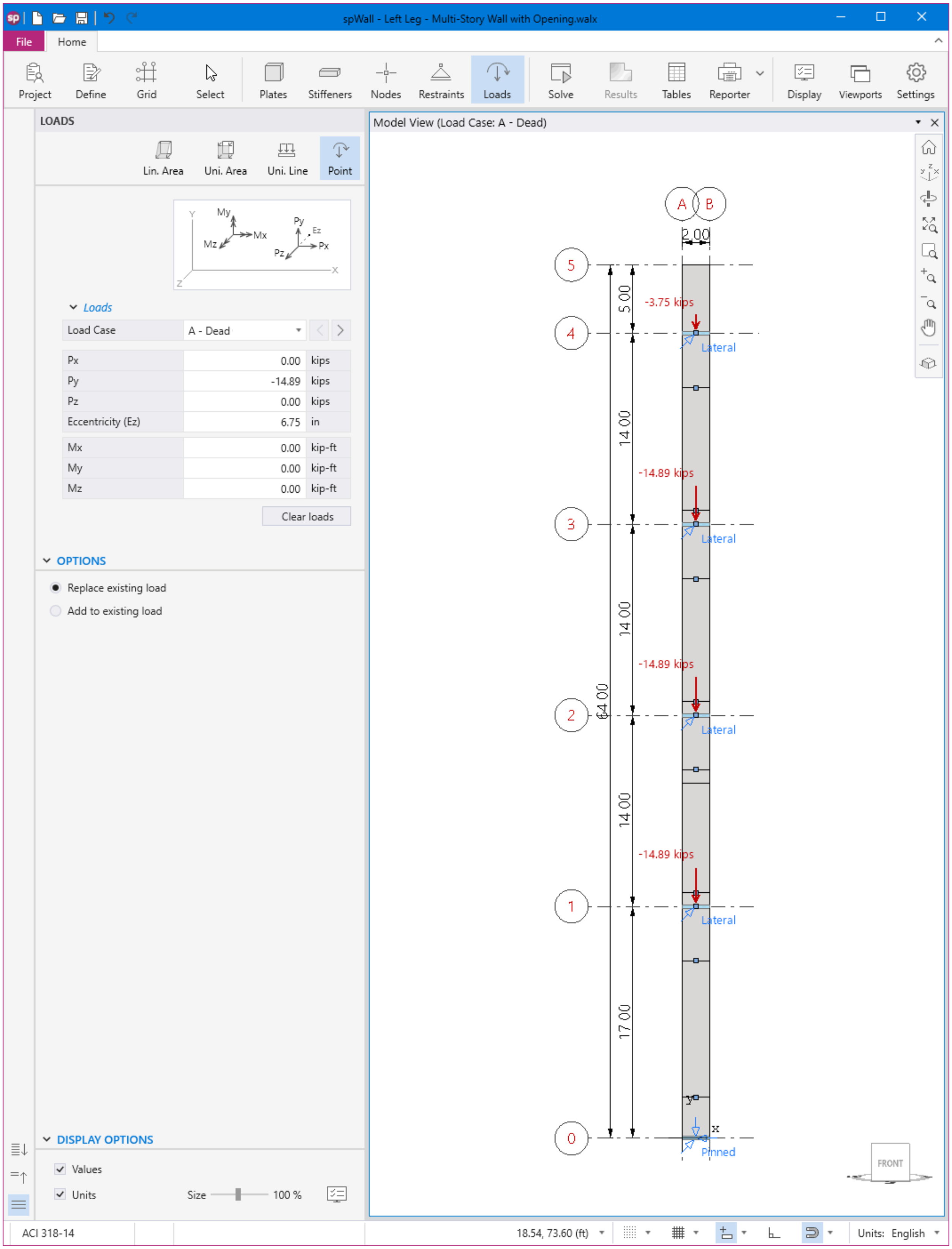


Figure 6 – Assigning Dead Loads for Multi-Story Tilt-Up Wall with Opening (spWall)

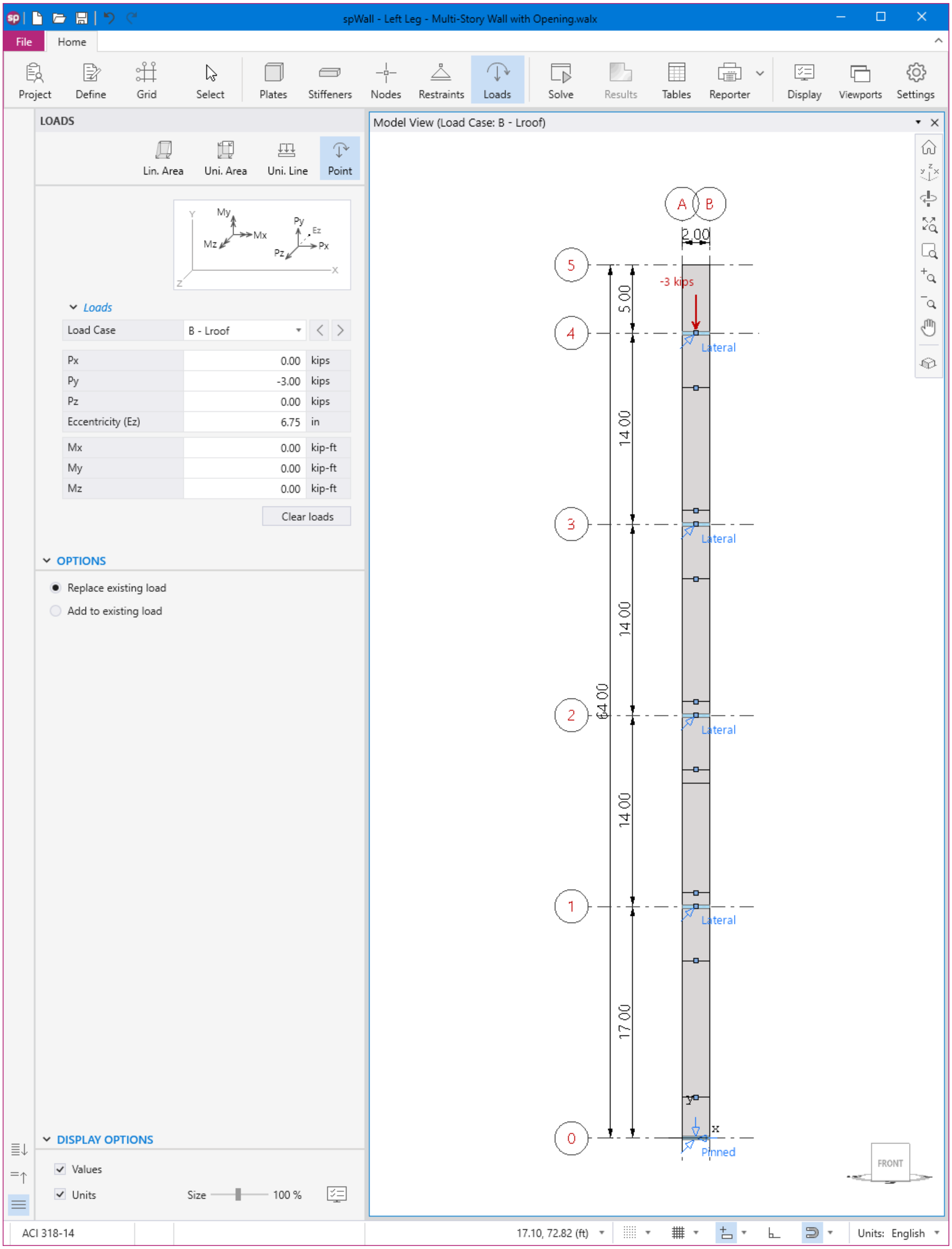


Figure 7 – Assigning Roof Live Loads for Multi-Story Tilt-Up Wall with Opening (spWall)

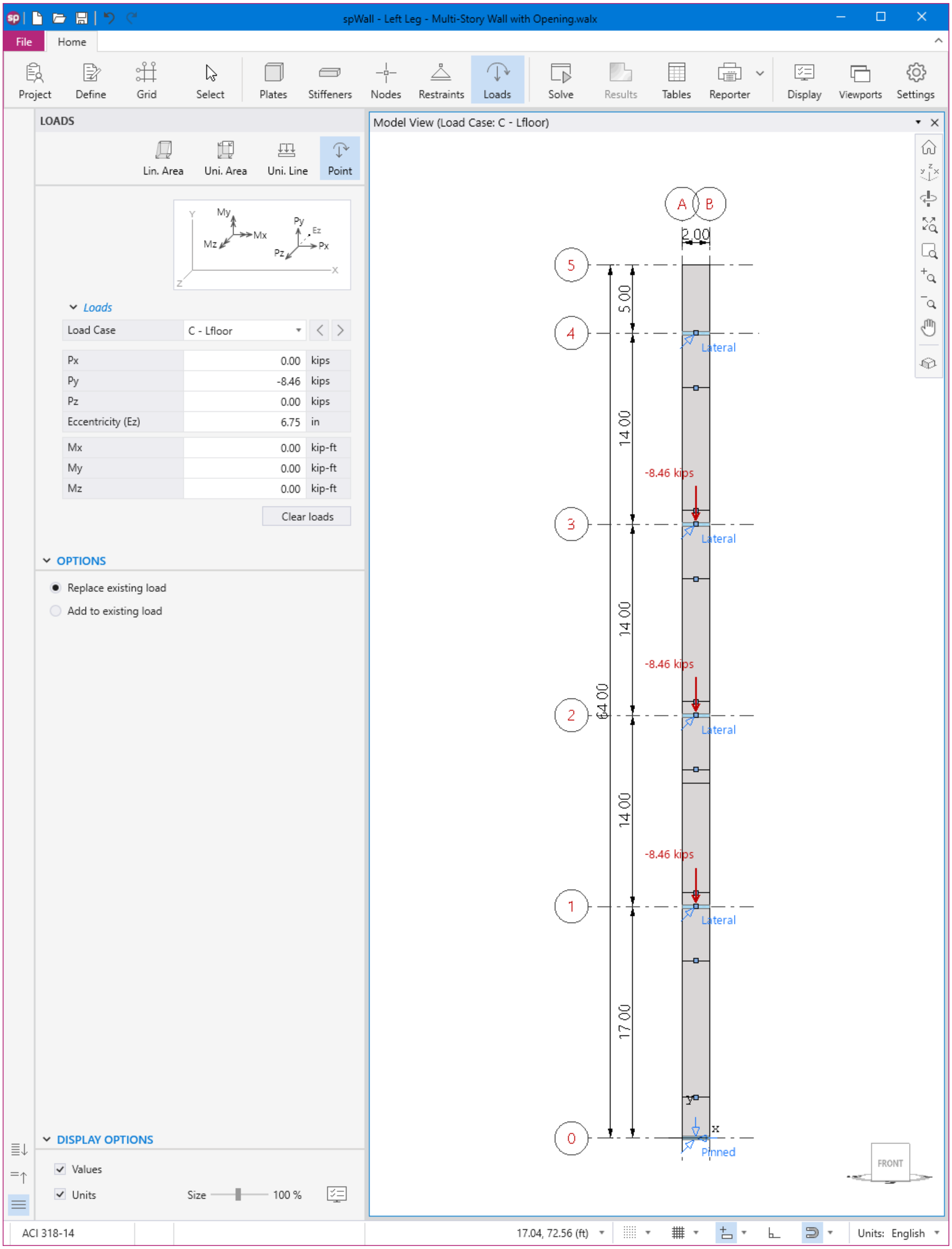


Figure 8 – Assigning Floor Live Loads for Multi-Story Tilt-Up Wall with Opening (spWall)

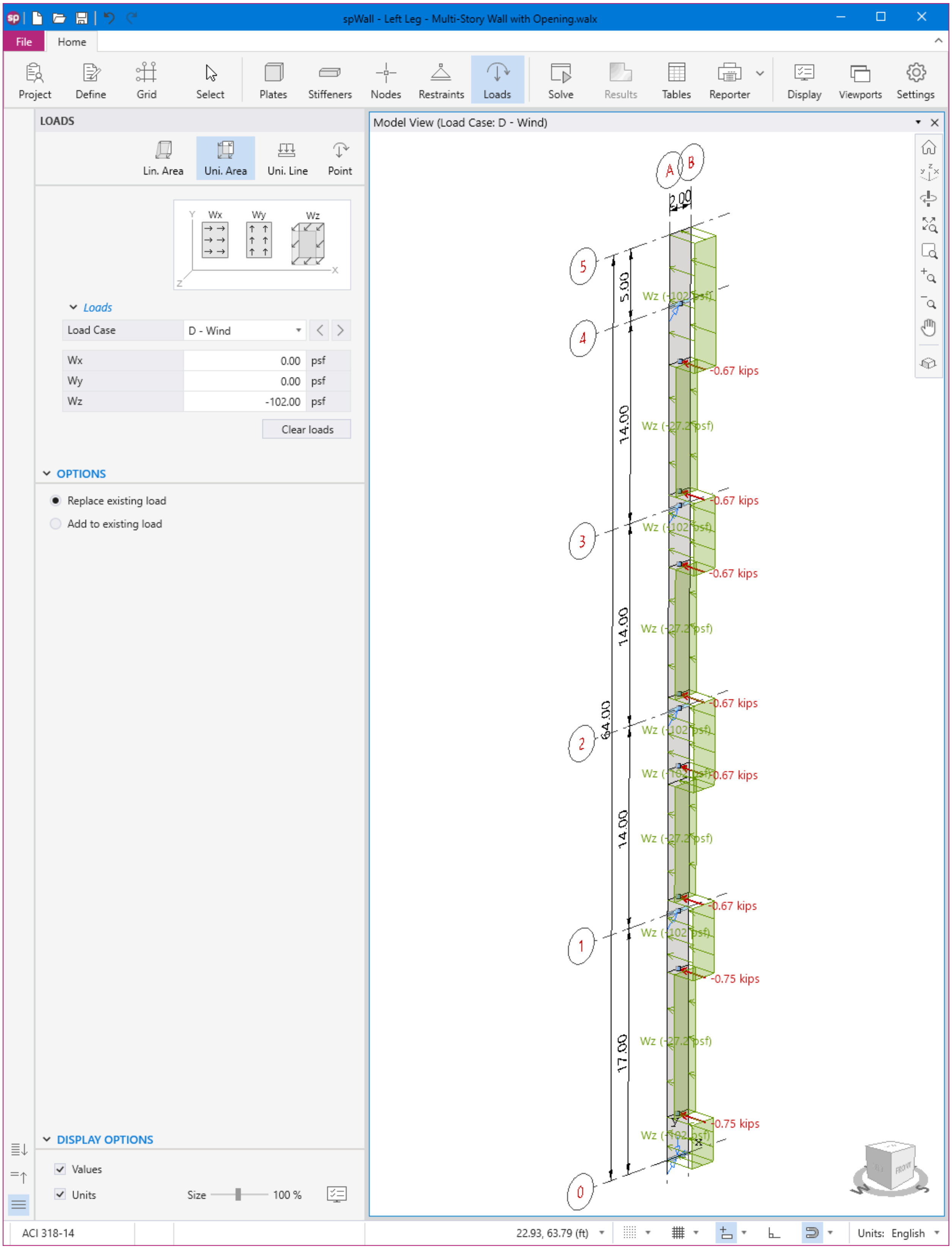


Figure 9 – Assigning Wind Loads for Multi-Story Tilt-Up Wall with Opening (spWall)

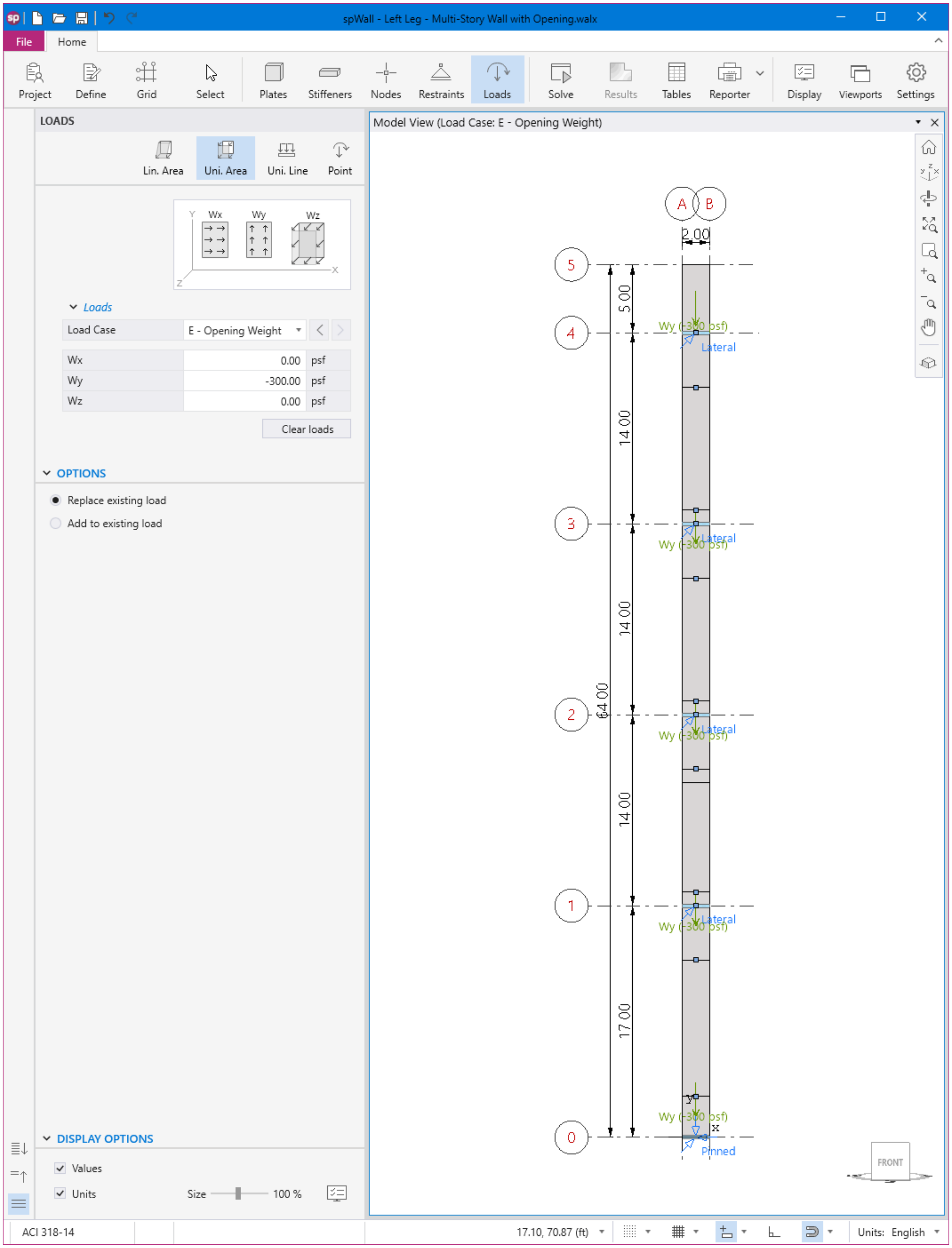


Figure 10 – Assigning Opening Weight Loads for Multi-Story Tilt-Up Wall with Opening (spWall)

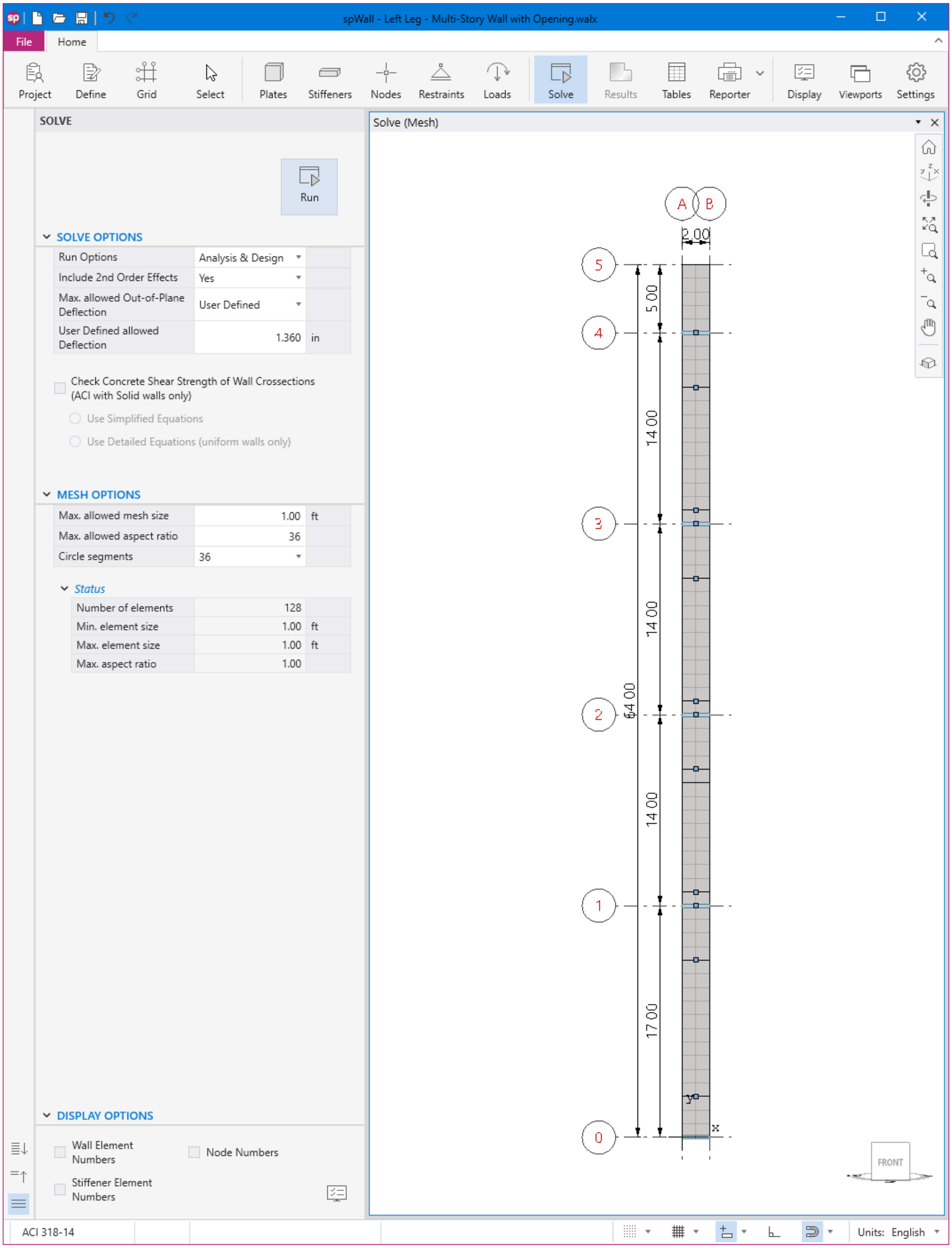


Figure 11 – Solve and Mesh Options (spWall)

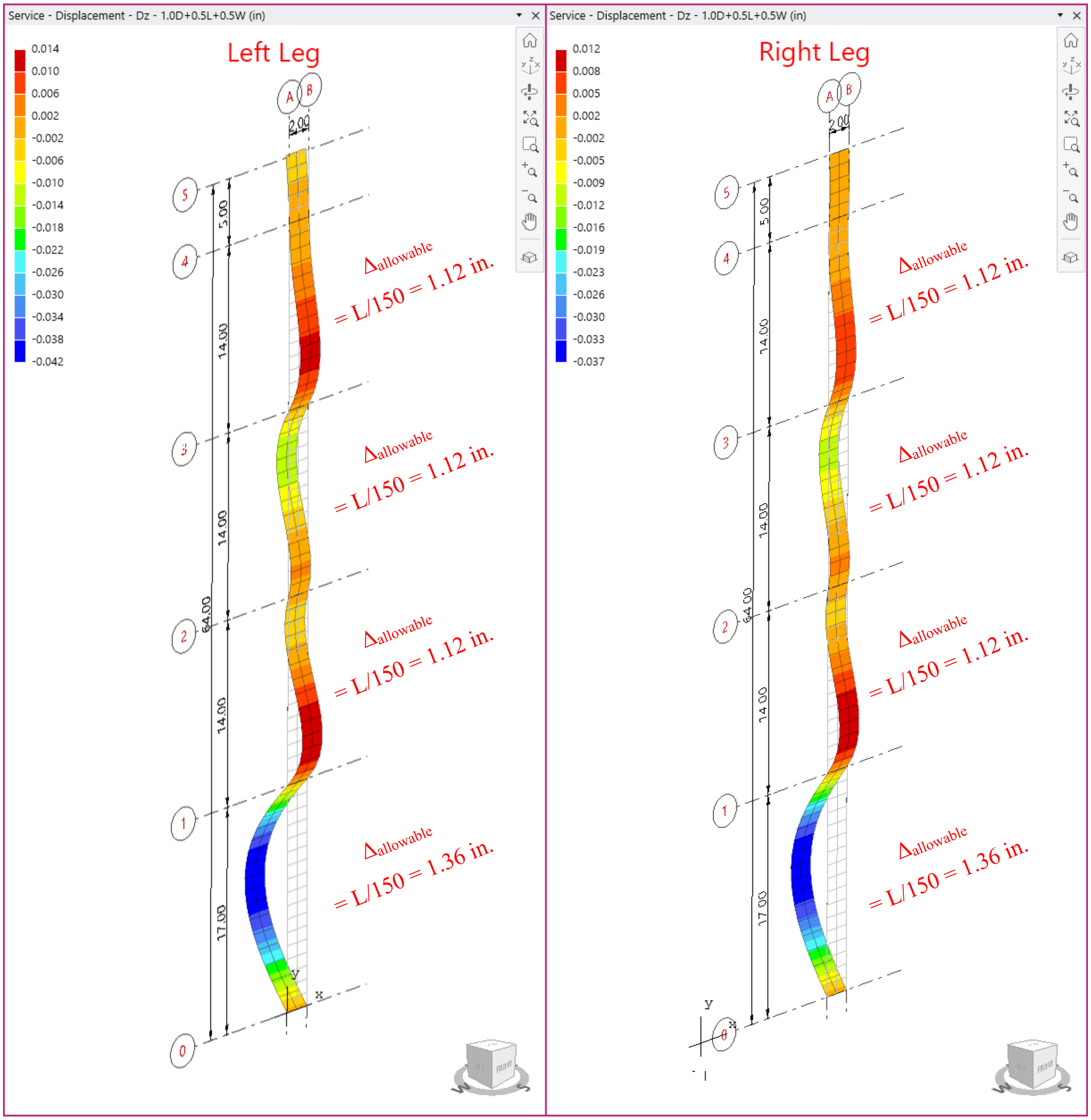


Figure 12 – Tilt-Up Design Strip Service Displacements (in.) (spWall)

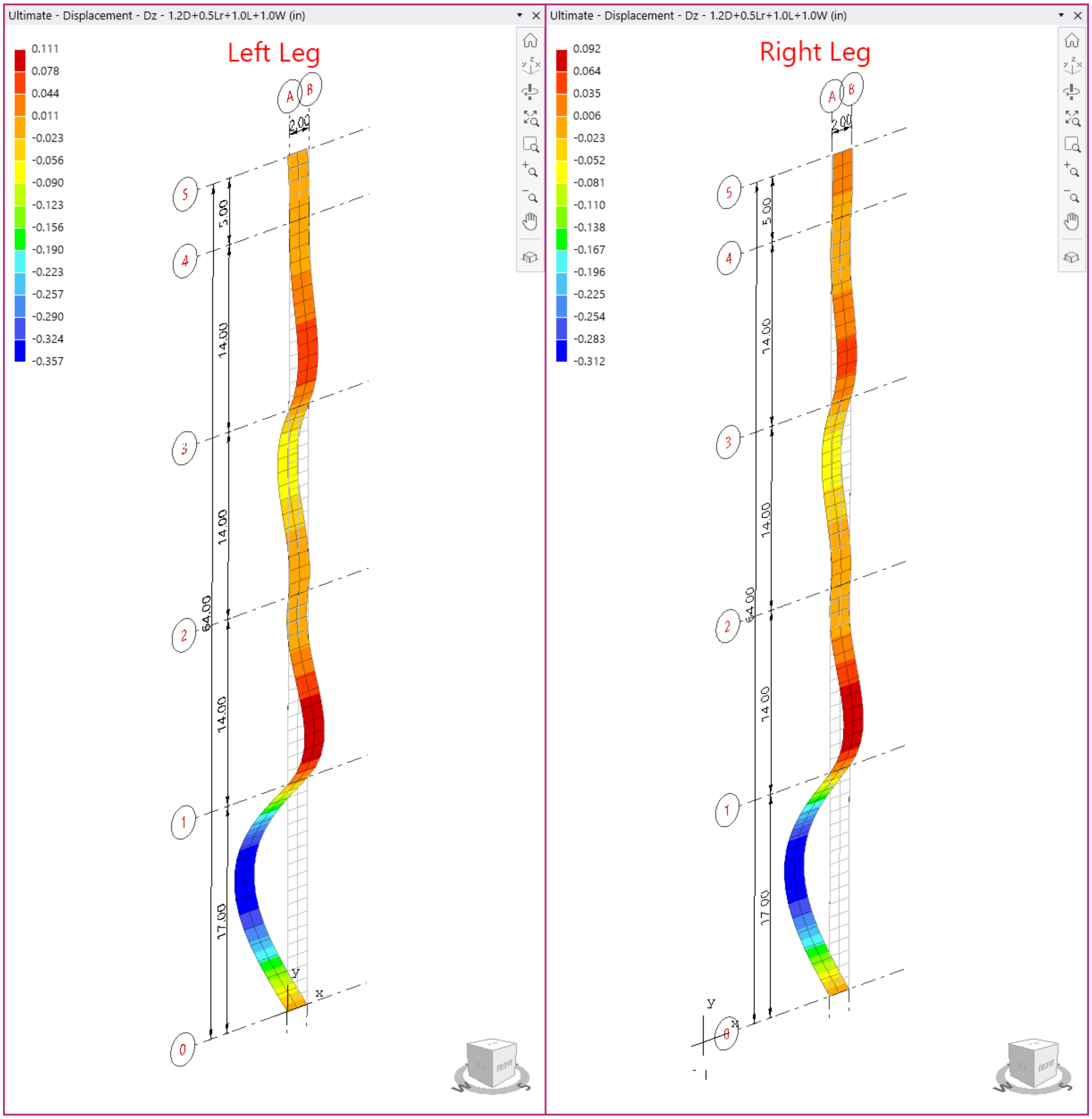


Figure 13 – Tilt-Up Design Strip Ultimate Displacements (in.) (spWall)

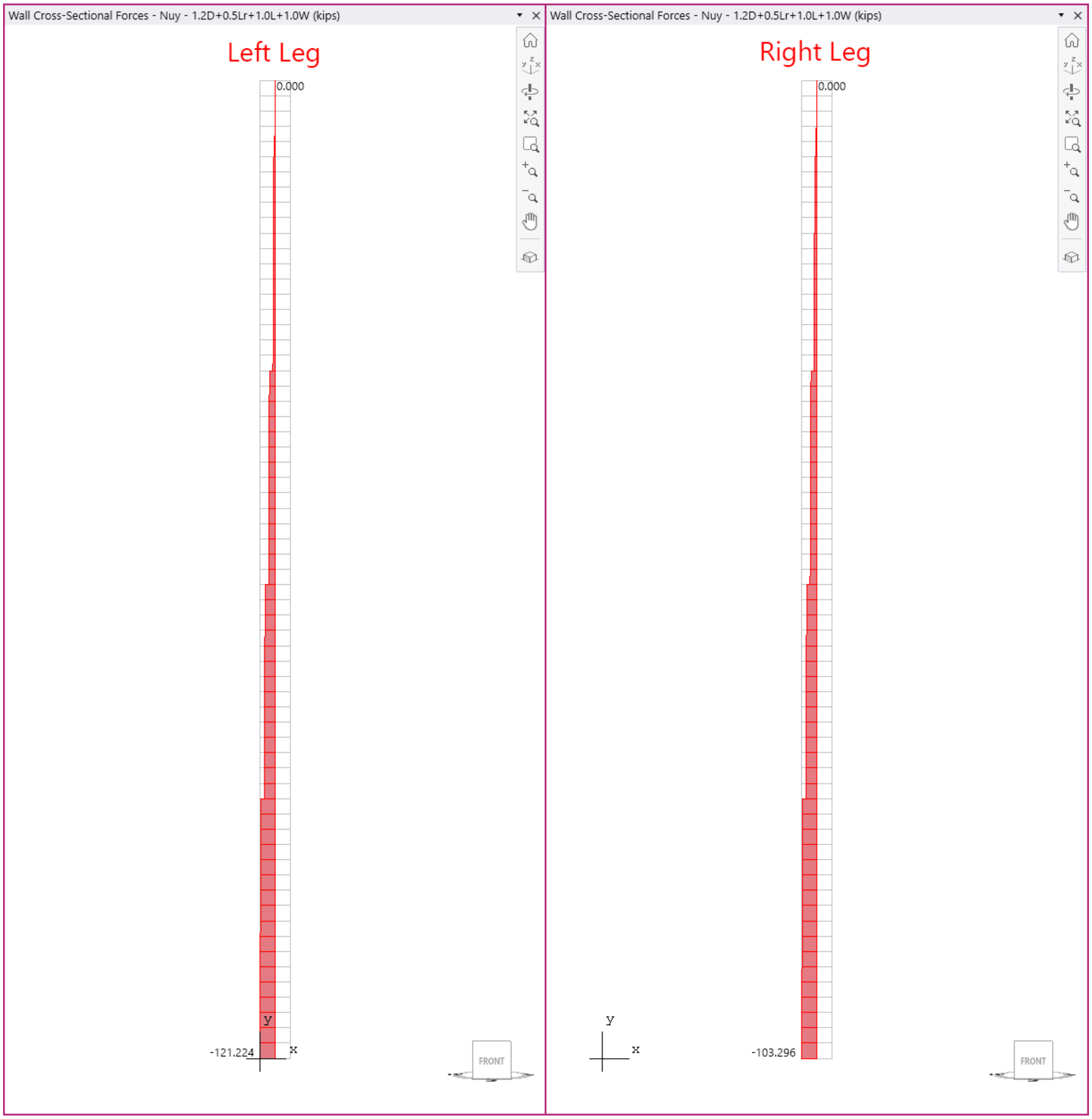


Figure 14 – Axial Force Diagram (kips) (spWall)

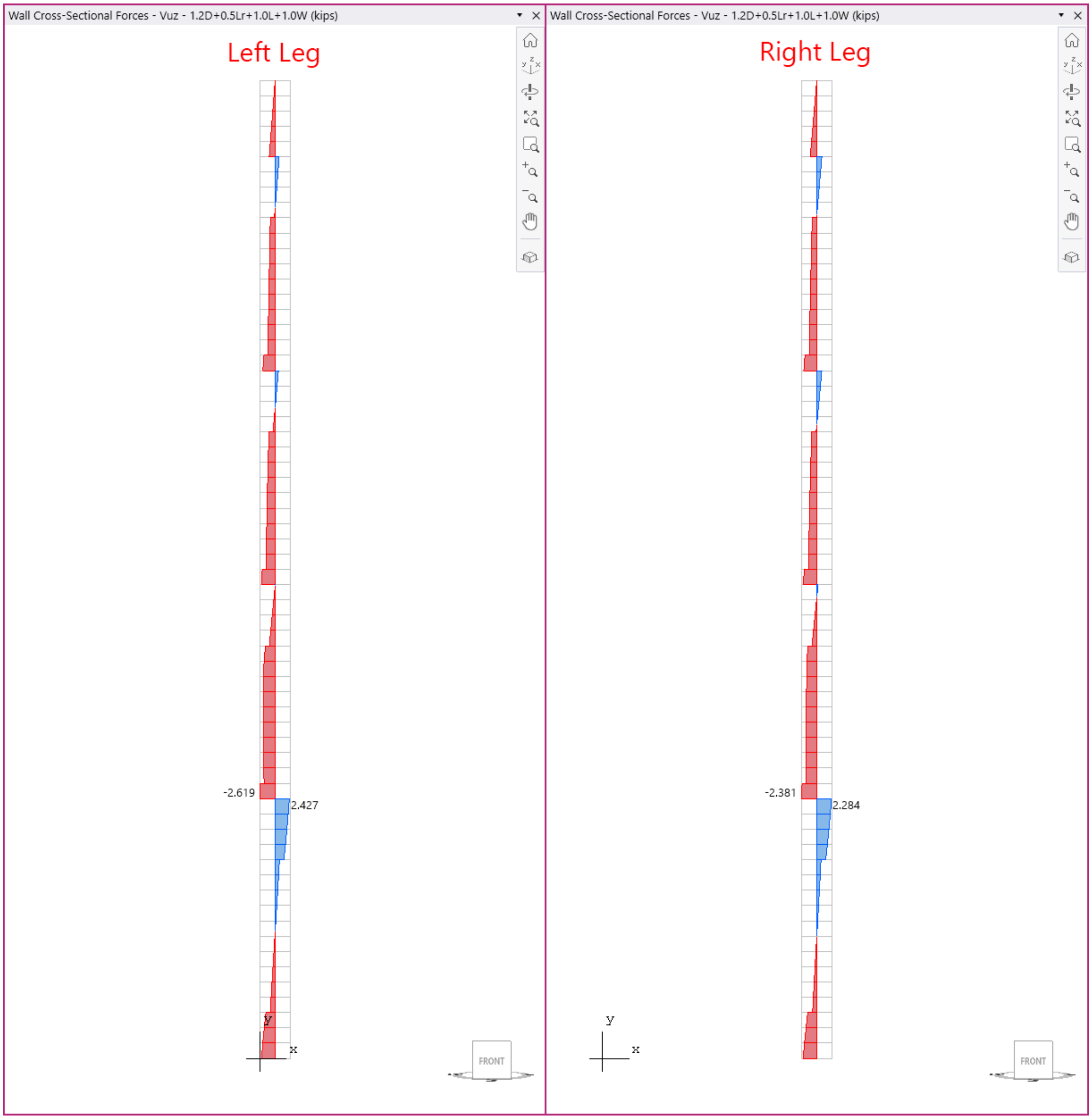


Figure 15 – Out-of-Plane Shear Force Diagram (kips) (spWall)

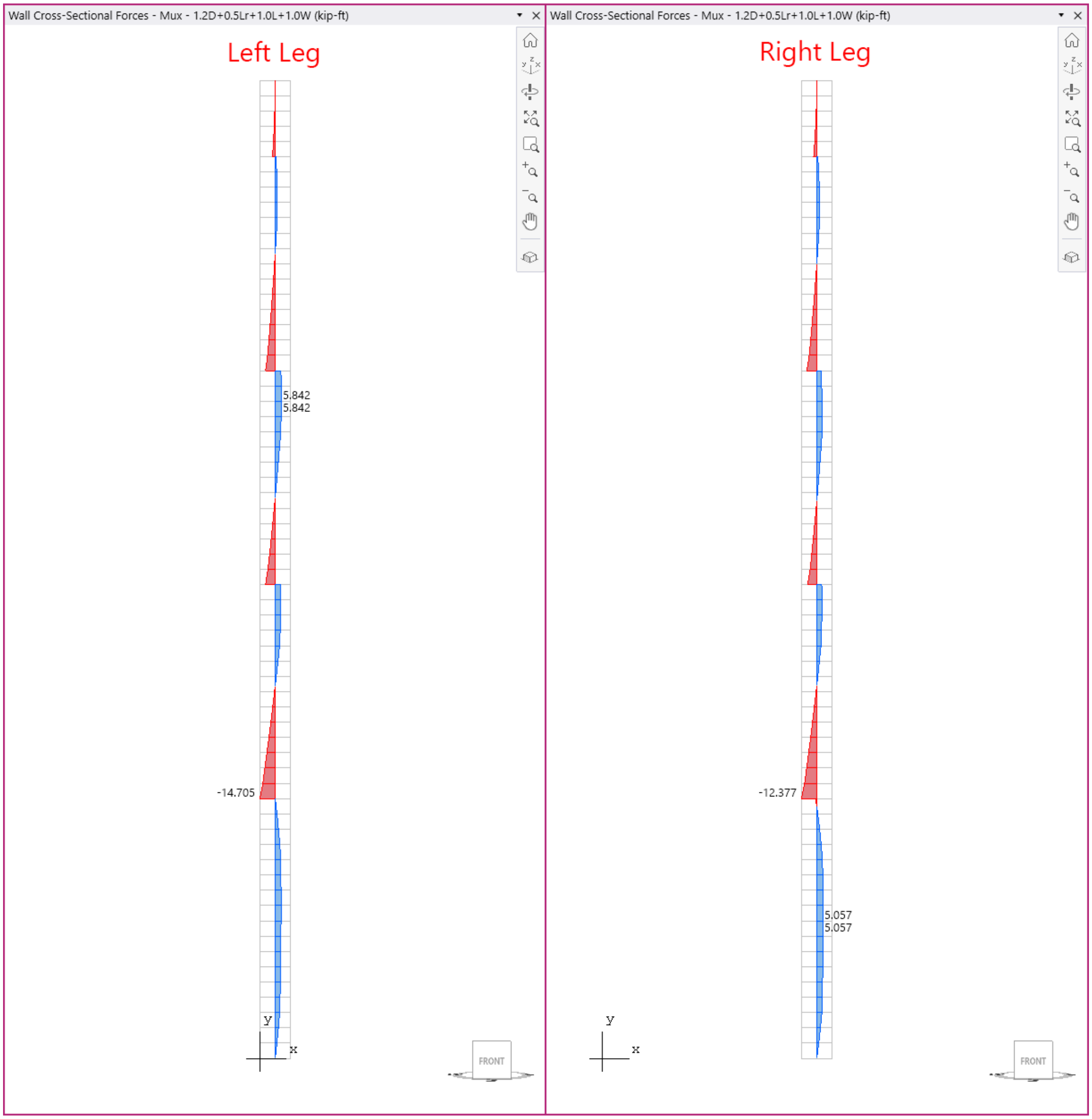


Figure 16 – First Order Bending Moment Diagram (kip-ft) (spWall)

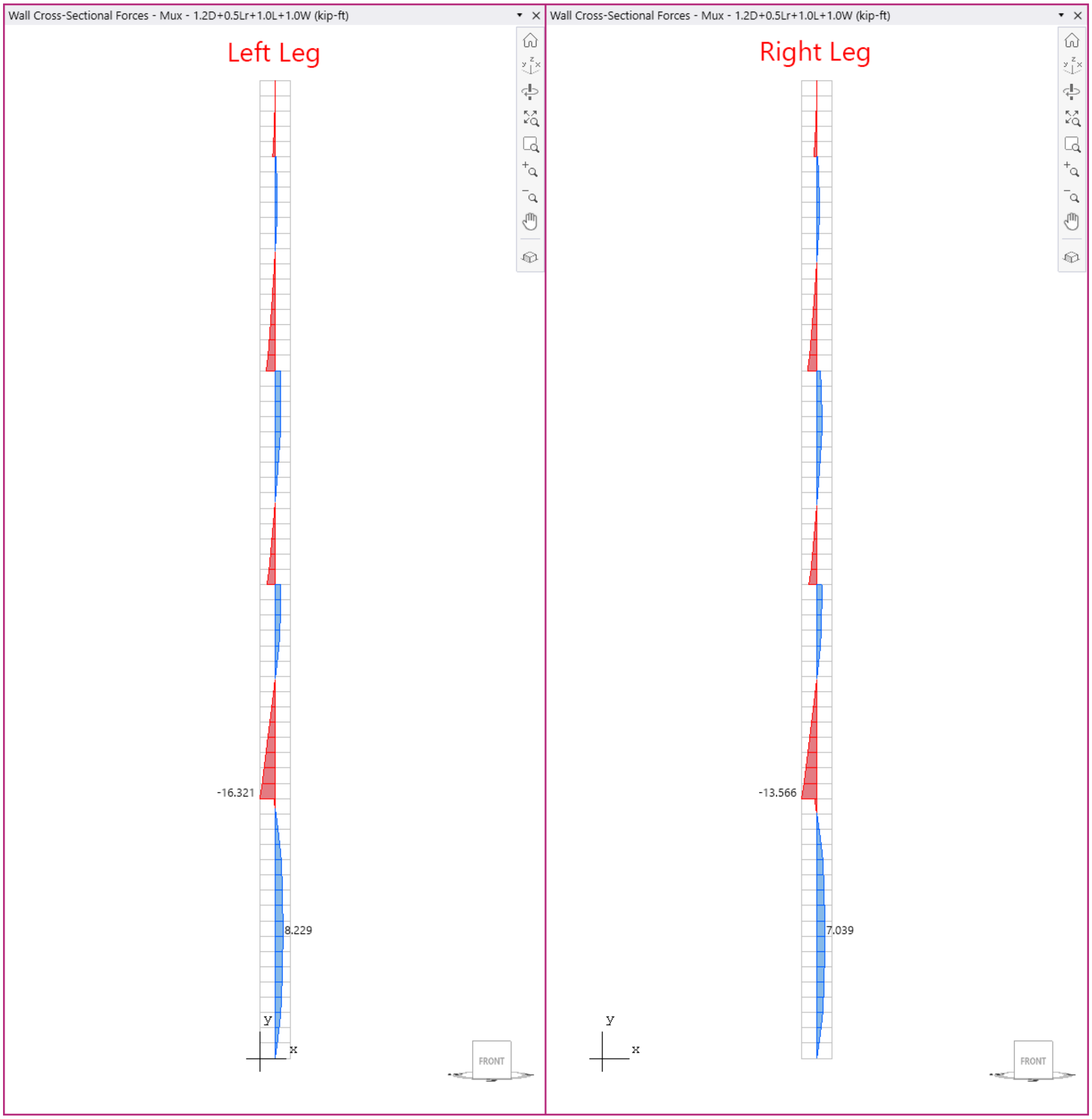


Figure 17 – Second Order Bending Moment Diagram (kip-ft) (spWall)

1. Results

1.1. Ultimate

1.1.1. Nodal Displacements

Left Leg

1.1.1.1. 1.2D+0.5Lr+1.0L+1.0W

Coordinate System: Global

Section	Node	Dx (in)	Dy (in)	Dz (in)	
8 ft	25	0.000	-0.015	-0.357	$D_{z,avg}$ = 0.357 in.
	26	0.000	-0.015	-0.356	
	27	0.000	-0.015	-0.357	
17 ft	52	0.000	-0.031	0.000	$D_{z,avg}$ = 0.000 in.
	53	0.000	-0.032	0.000	
	54	0.000	-0.031	0.000	
43 ft	130	0.000	-0.059	-0.055	$D_{z,avg}$ = 0.055 in.
	131	0.000	-0.059	-0.054	
	132	0.000	-0.059	-0.055	

1. Results

1.1. Ultimate

1.1.1. Nodal Displacements

Right Leg

1.1.1.1. 1.2D+0.5Lr+1.0L+1.0W

Coordinate System: Global

Section	Node	Dx (in)	Dy (in)	Dz (in)	
8 ft	25	0.000	-0.013	-0.312	$D_{z,avg}$ = 0.312 in.
	26	0.000	-0.013	-0.311	
	27	0.000	-0.013	-0.312	
17 ft	52	0.000	-0.026	0.000	$D_{z,avg}$ = 0.000 in.
	53	0.000	-0.027	0.000	
	54	0.000	-0.026	0.000	
41 ft	124	0.000	-0.049	-0.064	$D_{z,avg}$ = 0.064 in.
	125	0.000	-0.049	-0.063	
	126	0.000	-0.049	-0.064	

Figure 18 – Ultimate Displacement at Critical Sections (spWall)

1.1.2. Wall Cross-Sectional Forces

1.1.2.1. 1.2D+0.5Lr+1.0L+1.0W

Left Leg

Coordinate System: Global
(+) Horizontal cross-section above Y-coordinate
(-) Horizontal cross-section below Y-coordinate

Wall Crossection			In-Plane Forces			Out-Of-Plane Forces		
No.	Y coordinate	X-Centroid	Vux	Nuy	Muz	Vuz	Mux	Muy
	ft	ft	kips	kips	kip-ft	kips	kip-ft	kip-ft
9-	8.00	1.00	0.00	-116.96	0.00	-0.05	8.23	0.00
9+	8.00	1.00	0.00	-116.96	0.00	-0.05	8.23	0.00
18+	17.00	1.00	0.00	-85.39	0.00	-2.62	-16.32	0.00
44-	43.00	1.00	0.00	-46.48	0.00	0.09	5.92	0.00
44+	43.00	1.00	0.00	-46.48	0.00	0.09	5.93	0.00

1.1.2. Wall Cross-Sectional Forces

1.1.2.1. 1.2D+0.5Lr+1.0L+1.0W

Right Leg

Coordinate System: Global
(+) Horizontal cross-section above Y-coordinate
(-) Horizontal cross-section below Y-coordinate

Wall Crossection			In-Plane Forces			Out-Of-Plane Forces		
No.	Y coordinate	X-Centroid	Vux	Nuy	Muz	Vuz	Mux	Muy
	ft	ft	kips	kips	kip-ft	kips	kip-ft	kip-ft
9-	8.00	14.00	0.00	-99.04	0.00	0.00	7.04	0.00
9+	8.00	14.00	0.00	-99.04	0.00	0.00	7.04	0.00
18+	17.00	14.00	0.00	-73.44	0.00	-2.38	-13.57	0.00
42-	41.00	14.00	0.00	-42.47	0.00	-0.78	4.55	0.00
42+	41.00	14.00	0.00	-42.47	0.00	-0.11	4.55	0.00

Figure 19 – Cross-Sectional Forces at Critical Sections (spWall)

7. Design Results Comparison and Conclusions

The model shown above was created in spWall considering the ACI 318-14 provisions (Alternative Method for Out-of-Plane Slender Wall Analysis) and ACI 551 recommendations regarding the analysis and design of tilt-up wall panels with openings. In this model the left and right design strips are modeled such that the entire lateral and axial load, including self-weight above the critical section, are distributed to the two strips as idealized in Section 1. The following table shows the comparison between hand results with spWall model results.

Table 4 – Comparison of Tilt-Up Wall Panel with Opening Analysis and Design Results

Output	Location (ft)	Design Strip	Solution	
			Hand	spWall
M_u (kip-ft)	8 (+ve)	Left	7.15	8.23
		Right	6.30	7.04
	17 (-ve)	Left	-17.94	-16.32
		Right	-14.74	-13.57
	43 (+ve)	Left	6.57	5.93
		Right*	4.74	4.55
$D_{z,ult}$ (in.)	8 (+ve)	Left	0.284	0.357
		Right	0.255	0.312
	17 (-ve)	Left	0.000	0.000
		Right	0.000	0.000
	43 (+ve)	Left	0.188	0.055
		Right*	0.139	0.064

* Maximum positive moment occurs at 41 ft height for the right strip

The results of all the hand calculations used illustrated above are in agreement with the automated exact results obtained from the spWall program with observations, comments and recommendations discussed later in this section.

8. Comparison of Design Strip with Complete Wall Panel Analysis

ACI 318-14 provides the "Alternative Method for Out-of-Plane Slender Wall Analysis" as a simple and accurate option for analysis and design of simple walls meeting the method conditions. ACI 551 allows the use of this method for some cases were some of the method limitations do not meet where the results obtained are still within acceptable range. However, the combination of a multi-span continuous wall with the presence of openings brings a lot of challenges accompanied with the use of the alternative analysis method. To understand the wall behavior and adequately address strength and stability requirement, other methods such as finite element analysis can be used with panels similar to the one in this example that do not meet alternative design method conditions where continuous supports provides negative moments and maximum positive moment don't occur at midspan. Many other issues arise with panels not meeting the method limitations (continuous and cantilevered walls, variable thickness and width, walls with openings, non-standard boundary conditions, walls with high compressive loads, in-plane lateral loads, non-standard concentrated load position from attachments of piping, racking etc., concentrated out of plane loads).

In the following section, the complete tilt-up wall panel geometry and loads are employed for illustration and comparison.

9. Complete Wall Panel Analysis – spWall Software

The exact wall geometry and applied loads were modeled using spWall engineering software to investigate the differences between the simplified approximate method using design strips and the finite element method for the complete panel with openings. For illustration and comparison purposes, the following figures provide a sample of the results obtained from an spWall model created for the complete panel.

It is very important to consider the wind load applied to the windows openings and how it must be considered and applied in the model based on the windows boundary condition. In this example, the windows support reactions are applied along the top and bottom of the windows openings. Load is modeled as an equivalent uniform line load applied along the top and bottom opening grids. The magnitude of this load is calculated as follows:

$$W_{door} = 27.2 \times \frac{10}{2} \times \frac{1}{1000} = 0.136 \text{ kip/ft} \quad \text{for the 10' long window}$$

$$W_{door} = 27.2 \times \frac{9}{2} \times \frac{1}{1000} = 0.122 \text{ kip/ft} \quad \text{for the 9' long windows}$$

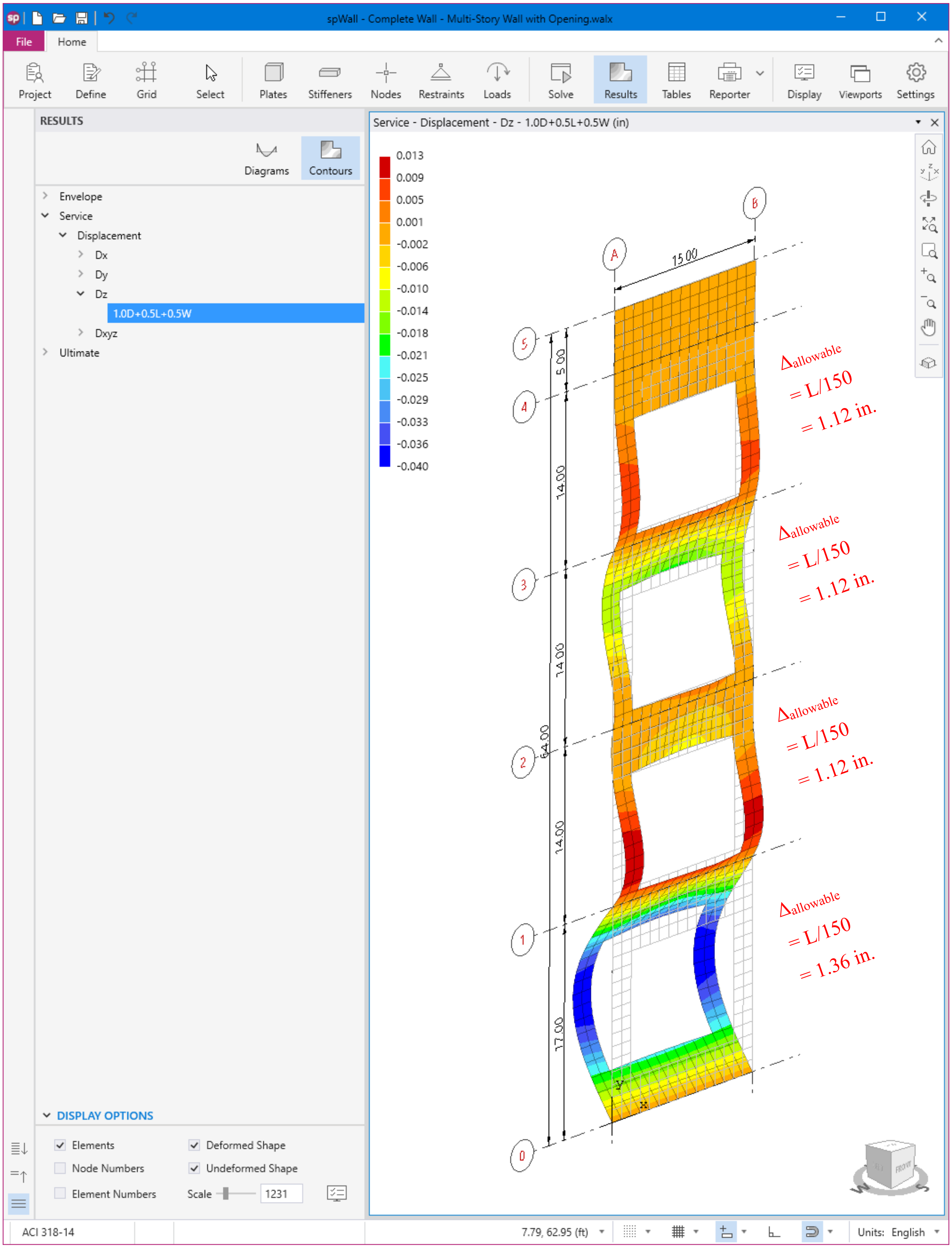


Figure 20 – Complete Wall Service Displacements (in.) (spWall)

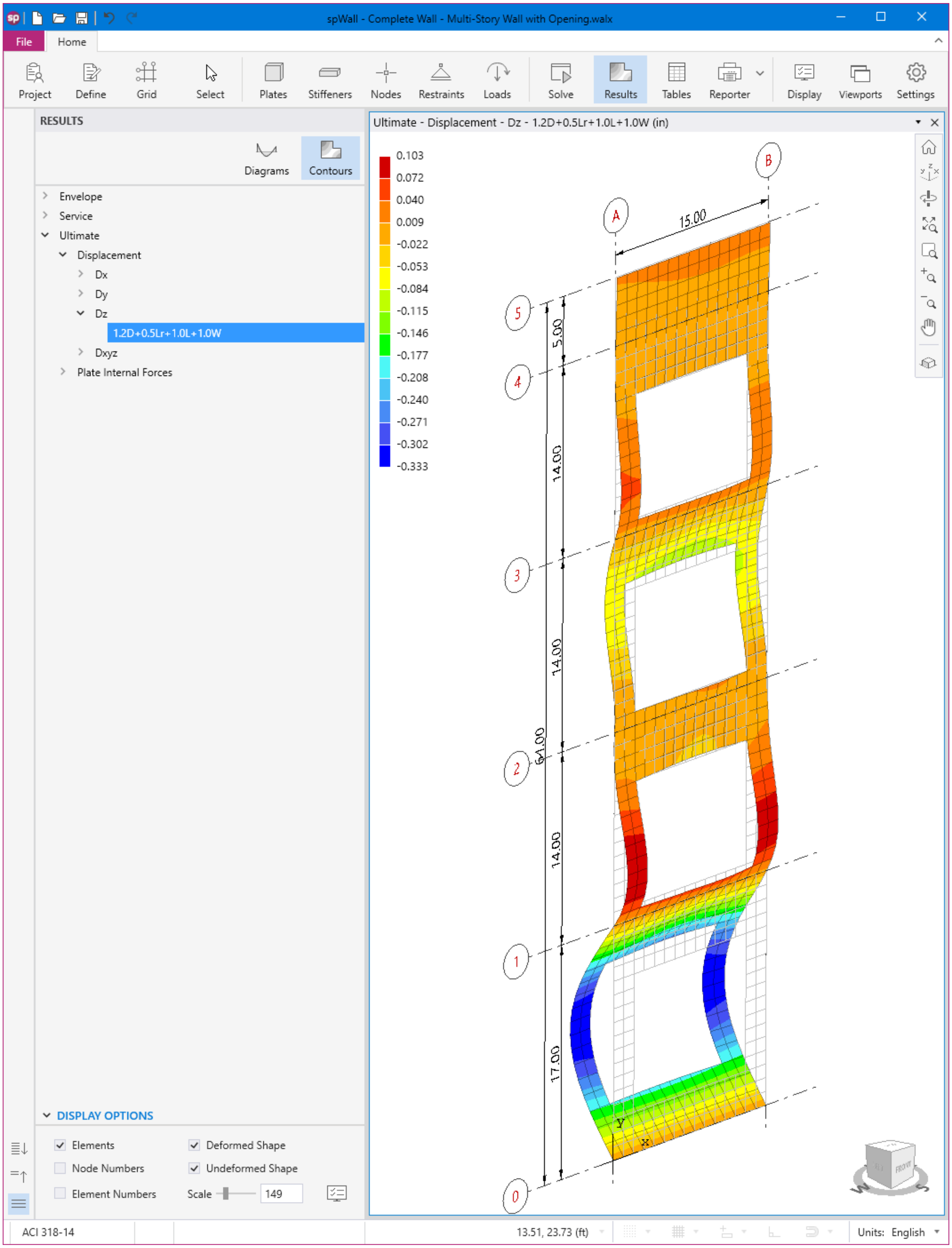


Figure 21 – Complete Wall Ultimate Displacements (in.) (spWall)

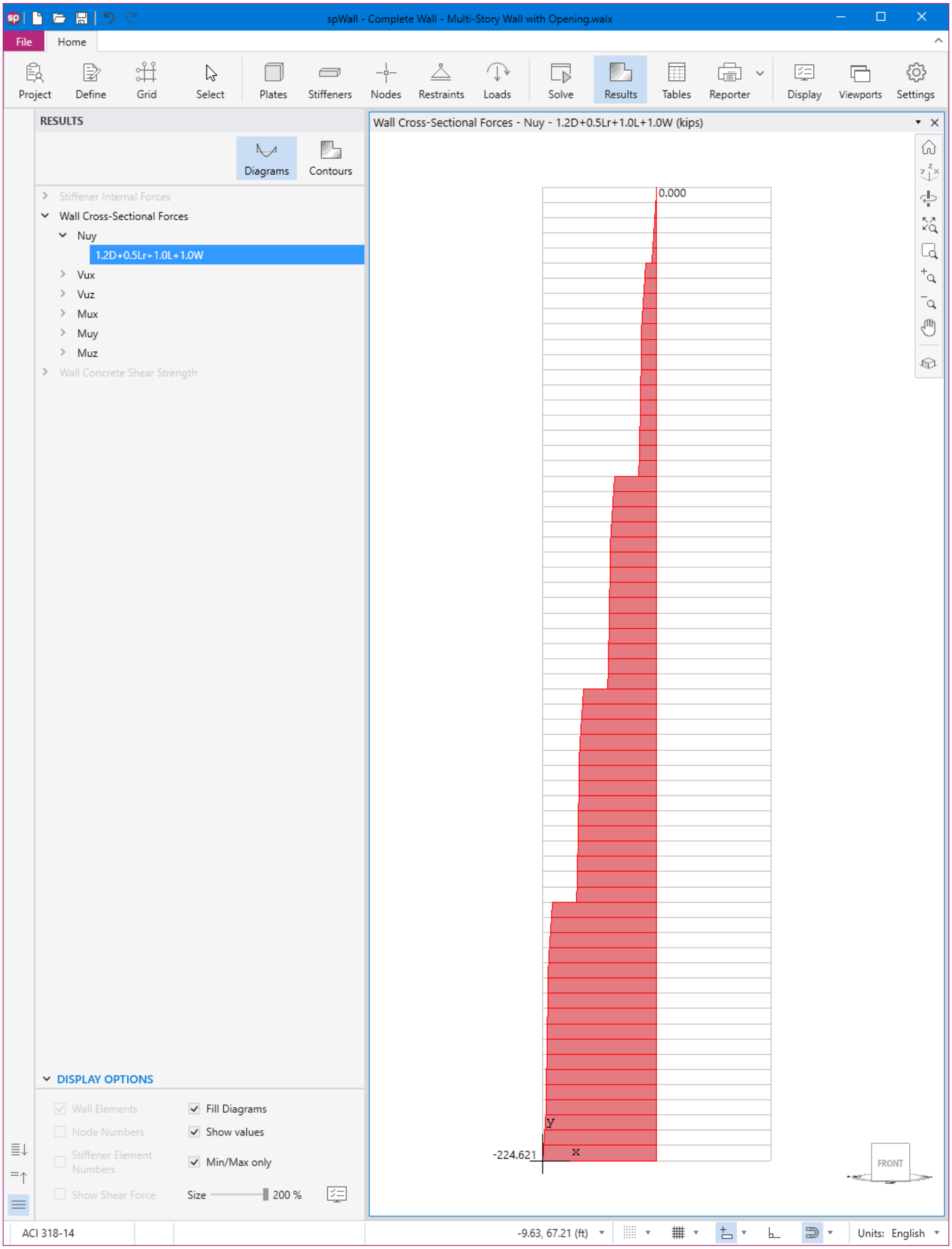


Figure 22 – Axial Force Diagram (kips) (spWall)

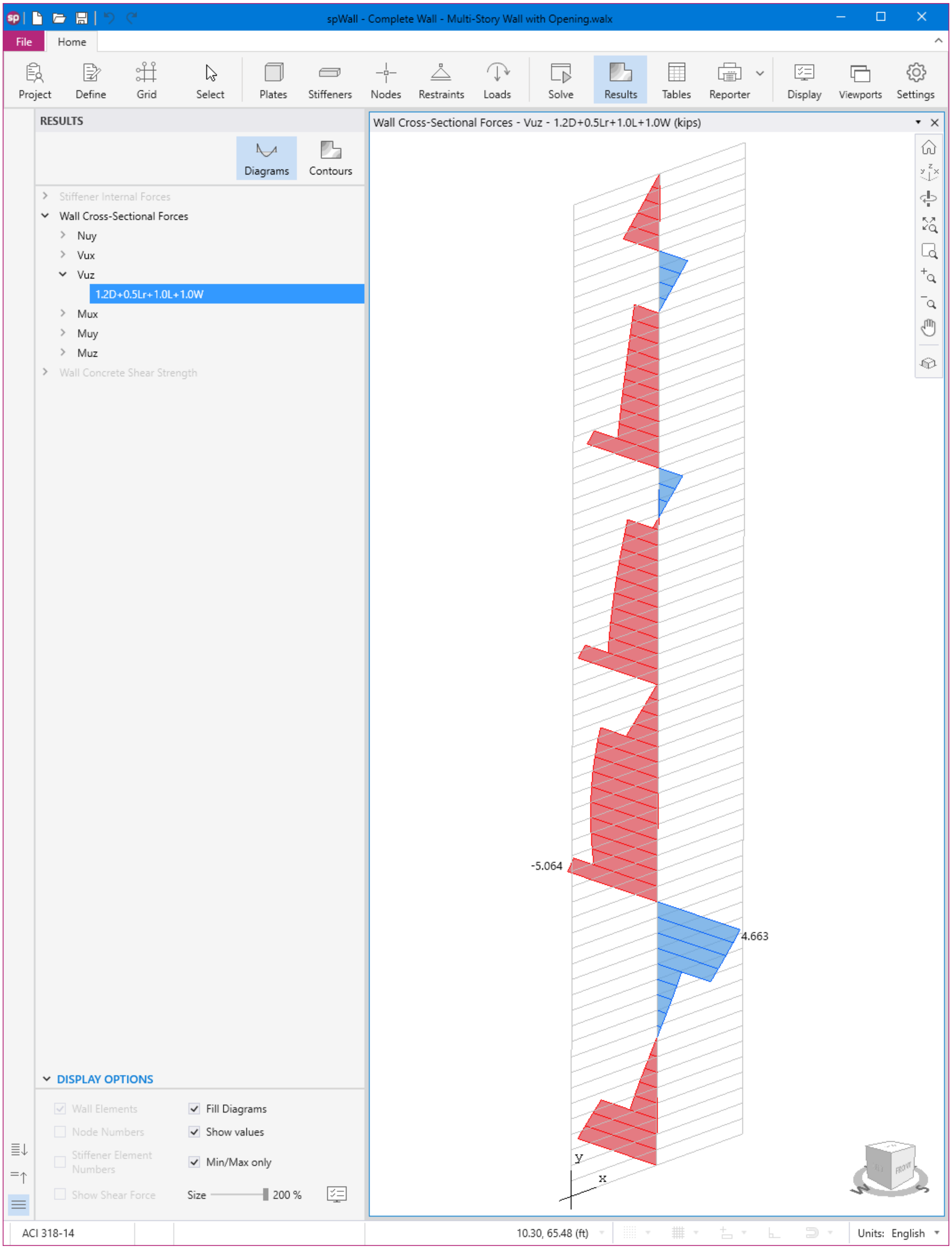


Figure 23 – Complete Wall Shear Force Diagram (kips) (spWall)

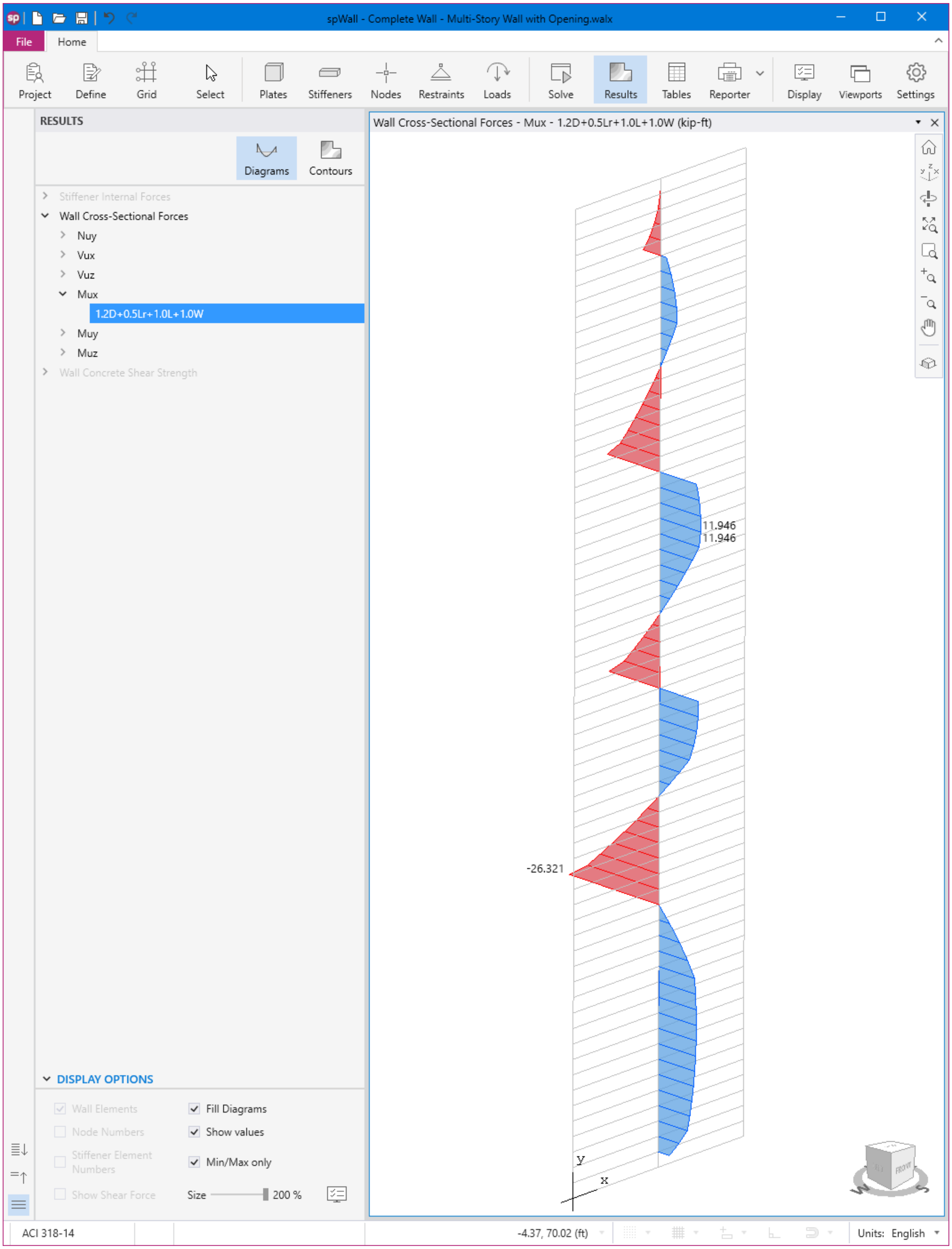


Figure 24 – Complete Wall First Order Moment Diagram (kip-ft) (spWall)

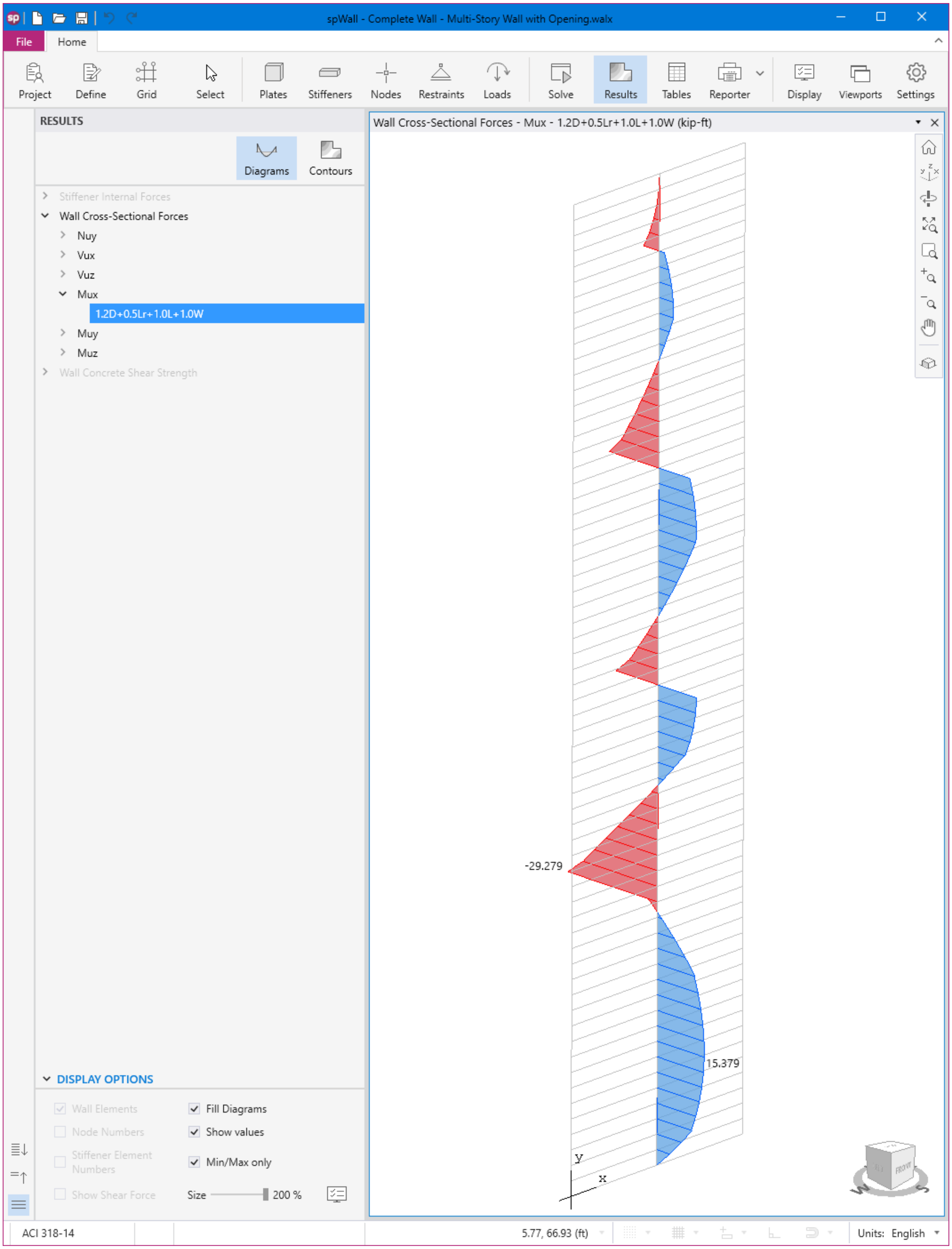


Figure 25 – Complete Wall Second Order Moment Diagram (kip-ft) (spWall)

1. Results
1.1. Ultimate
1.1.1. Nodal Displacements
1.1.1.1. 1.2D+0.5Lr+1.0L+1.0W

Coordinate System: Global

	Node	Dx	Dy	Dz	
		in	in	in	
8 ft	89	-0.008	-0.015	-0.328	$D_{z,avg}$ = 0.326 in.
	90	-0.008	-0.014	-0.329	
	91	-0.008	-0.014	-0.333	
	92	0.005	-0.012	-0.328	
	93	0.006	-0.012	-0.321	
	94	0.006	-0.012	-0.316	
17 ft	183	-0.004	-0.031	0.000	$D_{z,avg}$ = 0.000 in.
	184	-0.004	-0.029	0.000	
	185	-0.004	-0.028	0.000	
	186	-0.004	-0.028	0.000	
	187	-0.004	-0.028	0.000	
	188	-0.004	-0.028	0.000	
	189	-0.004	-0.028	0.000	
	190	-0.004	-0.029	0.000	
	191	-0.004	-0.029	0.000	
	192	-0.005	-0.029	0.000	
	193	-0.005	-0.028	0.000	
	194	-0.005	-0.027	0.000	
	195	-0.005	-0.026	0.000	
	196	-0.005	-0.025	0.000	
	197	-0.005	-0.024	0.000	
	198	-0.005	-0.024	0.000	
43 ft	439	-0.026	-0.056	-0.047	$D_{z,avg}$ = 0.052 in.
	440	-0.026	-0.056	-0.046	
	441	-0.025	-0.056	-0.045	
	442	-0.025	-0.056	-0.047	
	443	-0.026	-0.056	-0.049	
	444	-0.026	-0.056	-0.052	
	445	-0.026	-0.055	-0.056	
	446	-0.026	-0.055	-0.059	
	447	-0.025	-0.055	-0.061	
	448	-0.025	-0.054	-0.063	
	449	-0.025	-0.053	-0.062	
	450	-0.025	-0.052	-0.058	
	451	-0.025	-0.050	-0.052	
	452	-0.025	-0.048	-0.047	
	453	-0.025	-0.047	-0.042	
	454	-0.025	-0.045	-0.038	

Figure 26 – Displacement at Critical Sections – Exact Geometry and Loads (Ultimate Combinations) (spWall)

1.1.2. Wall Cross-Sectional Forces

1.1.2.1. 1.2D+0.5Lr+1.0L+1.0W

Coordinate System: Global
(+) Horizontal cross-section above Y-coordinate
(-) Horizontal cross-section below Y-coordinate

Wall Crossection			In-Plane Forces			Out-Of-Plane Forces		
No.	Y coordinate	X-Centroid	Vux	Nuy	Muz	Vuz	Mux	Muy
	ft	ft	kips	kips	kip-ft	kips	kip-ft	kip-ft
9-	8.00	7.50	0.00	-216.09	116.70	-0.08	15.38	-0.38
9+	8.00	7.50	0.00	-216.09	117.04	-0.08	15.37	-0.38
18+	17.00	7.50	0.00	-158.91	78.12	-5.06	-29.28	-1.92
44-	43.00	7.50	0.00	-87.03	38.79	0.51	12.01	-1.69
44+	43.00	7.50	0.00	-87.03	39.13	0.51	12.00	-1.68

Figure 27 – Cross-Sectional Forces at Critical Sections – Exact Geometry and Loads (Ultimate Combinations) (spWall)

Table 5 – Comparison of Analysis Methods

Height (ft)	Solution	M_u (kip-ft)			$D_{z,ultimate}$ (in.)		
		Left	Right	Total	Left	Right	Total
8	Approximate Design Strips	8.23	7.04	15.27	0.357	0.312	0.335
	Complete Wall Model	---	---	15.38	0.330	0.322	0.326
17	Approximate Design Strips	-16.32	-13.57	-29.89	0.000	0.000	0.000
	Complete Wall Model	---	---	-29.28	0.000	0.000	0.000
43	Approximate Design Strips	5.93	4.32	10.25	0.055	0.044	0.050
	Complete Wall Model	---	---	12.01	0.050	0.053	0.052

From the table above, it can be observed that the complete wall deflections compare closely with the approximate design strips. However, the complete wall model requires fewer assumptions and approximations providing more reliable displacement estimates and better representation of the actual panel behavior.

10. Comments, Observations and Recommendations on the Current ACI 551 Procedure

The design guide for tilt-up concrete panels ACI 551 states that tilt-up concrete walls can be analyzed using the provisions of Chapter 14 of the ACI 318-11, the same provisions are presented in Chapter 11 of the ACI 318-14. Most walls, and especially slender walls, are widely evaluated using the "Alternative Method for Out-of-Plane Slender Wall Analysis" in Section 11.8 of the ACI 318-14. The method is applicable when the conditions summarized below are met:

- The wall can be designed as simply supported **ACI 318-14 (11.8.2.1)**
- The 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 cross section shall be constant over the height of the wall **ACI 318-14 (11.8.1.1(a))**
- 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 $0.06f_c'A_g$ **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(e))**

For multi-story panels with openings, ACI 551 utilized the alternative analysis method even though several of the conditions above are not met. This example identified important issues (related to the utilization of ACI 551 approach with multi-story panels with/without openings) summarized in the following figure. A detailed discussion of these issues can found in "Commentary on Multi-Story Tilt-Up Panel Design Using ACI 318-14 – ACI 551.2R-15" technical article in StructurePoint's technical articles page.

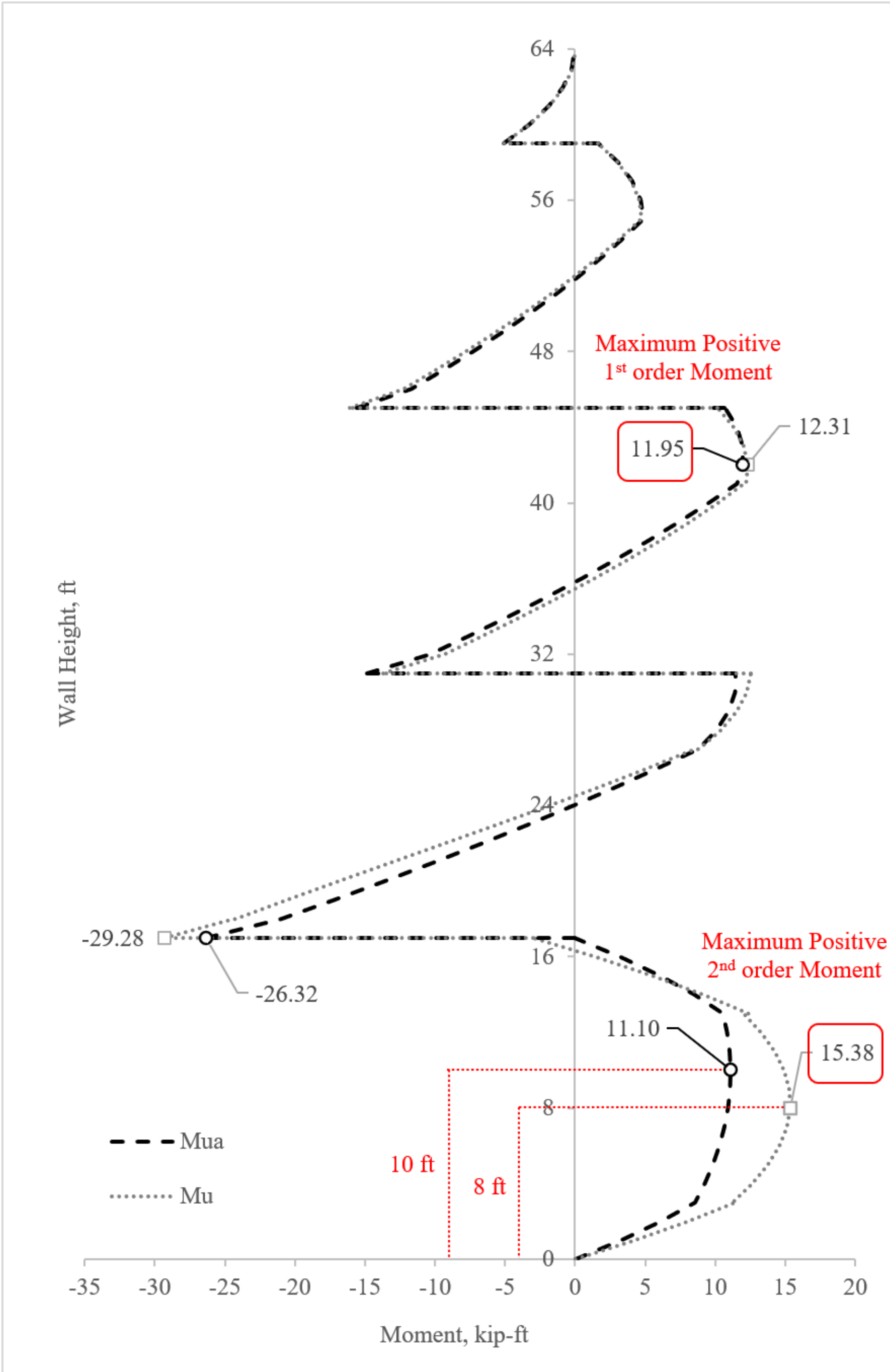


Figure 28 – First and Second Order Analysis (spWall)