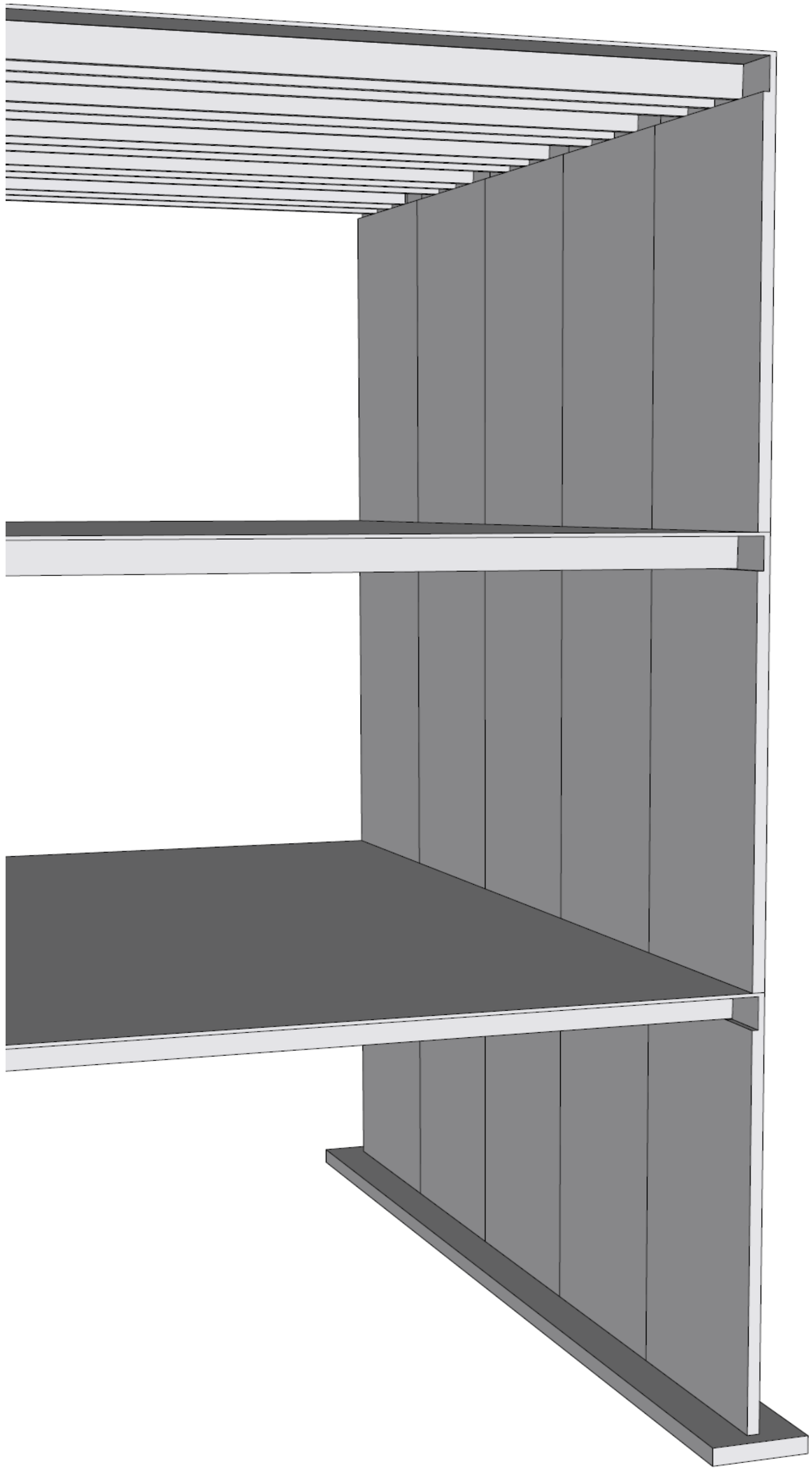
Multi-Story Solid Tilt-Up Wall Panel Analysis and Design (ACI 318-14 – ACI 551)



Reinforced Concrete Multi-Story Tilt-Up Wall Panel Analysis (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 tilt-up wall panel provides gravity and lateral load resistance in a multi-story building is covered in this Design Example (based on Example B.5 of ACI 551.2R-15). The assumed tilt-up wall panel section and reinforcement are investigated using the procedure provided by ACI 551.2R-15 and the provisions of ACI 318-14. Then compared with the results of spWall engineering software program from StructurePoint.

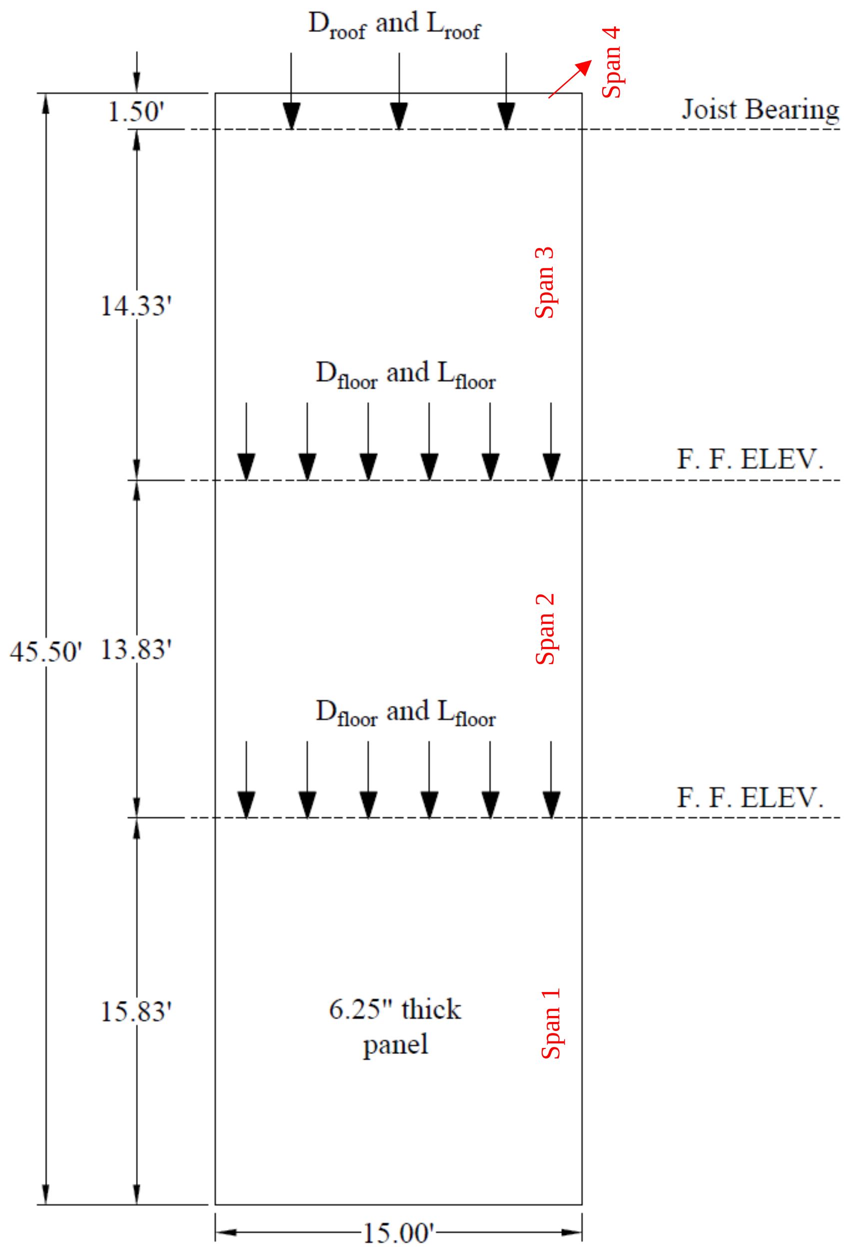


Figure 1 – Reinforced Concrete Multi-Story Tilt-Up Wall Panel Geometry

Content

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, Example B.5
- 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

Wall length = l_c = 45.5 ft – 1.5 ft = 44 ft

Assumed wall thickness = 6.25 in.

Assumed eccentricity = e_{cc} = 3 in.

Assumed vertical reinforcement: 11 #6 (one curtain)

1. Method of Solution

Multi-story tilt-up wall design is challenging compared with one-span (single-story) tilt-up wall. Selecting wall thickness is different than the typical single-story application, and can result in a much thinner section. Thus, stresses during construction and lifting should be investigated for the influence on required vertical reinforcement. The reference example examines the reinforcement required for the final in-service condition only.

According to ACI 551, continuous wall panels maybe analyzed and designed using the alternative analysis method in ACI 318.

For the three-span continuous tilt-up wall panel in this example, a structural analysis is required to obtain bending moments and shear forces. The first order moment diagram for load combination 1 can be obtained using any advanced structural analysis method, the details of the first order structural analysis are not covered in the example as published.

The reference example covers the same wall with two reinforcement configurations:

Configuration 1: Reinforcement centered in the wall thickness (singly reinforced – one curtain)

Configuration 2: Reinforcement at each face (doubly reinforced – two curtains)

Also, three load combinations are covered:

Load combination 1: $1.2D + 1.6L_r + 0.5W$

Load combination 2: $1.2D + 0.5L_r + 1.0L + 1.0W$

Load combination 3: $0.9D + 1.0W$

According to the reference, the maximum positive moment will occur in span 3 and the maximum negative moment will occur at the first floor level between spans 1 and 2.

For this example, calculating for load combination 1 with one curtain is illustrated to prevent repeated calculations. The calculations for different reinforcement configurations, load combinations and critical sections are the same and can be found in the reference.

2. Tilt-Up Wall Structural Analysis

2.1. Loads and Load Combinations

Roof dead load	= 3 × 2.4 = 7.20 kip
Roof live load	= 3 × 2.5 = 7.50 kip
Floor dead load	= 6 × 2.95 = 17.70 kip
Floor live load	= 6 × 5.0 = 30.00 kip
Wind load	= 27.2 psf (out of plane)
	= 0.00 psf (in plane)

$$\text{Wall self-weight} = \frac{6.25}{12}\times 15\times\left(45.5-15.8-13.8-11.2\right)\times 150\times\frac{1\text{ kip}}{1000\text{ lb}} = 5.51\text{ kip}$$

Self-weight is calculated at the critical section where the maximum positive moment is located at 11.2 ft above the second floor level in span 3. This information was obtained from the first order moment diagram shown in the next section.

2.2. Wall First Order Structural Analysis

Using the loads calculated in the previous section for load combination 1, the first order moment diagram can be obtained using any advanced structural analysis method.

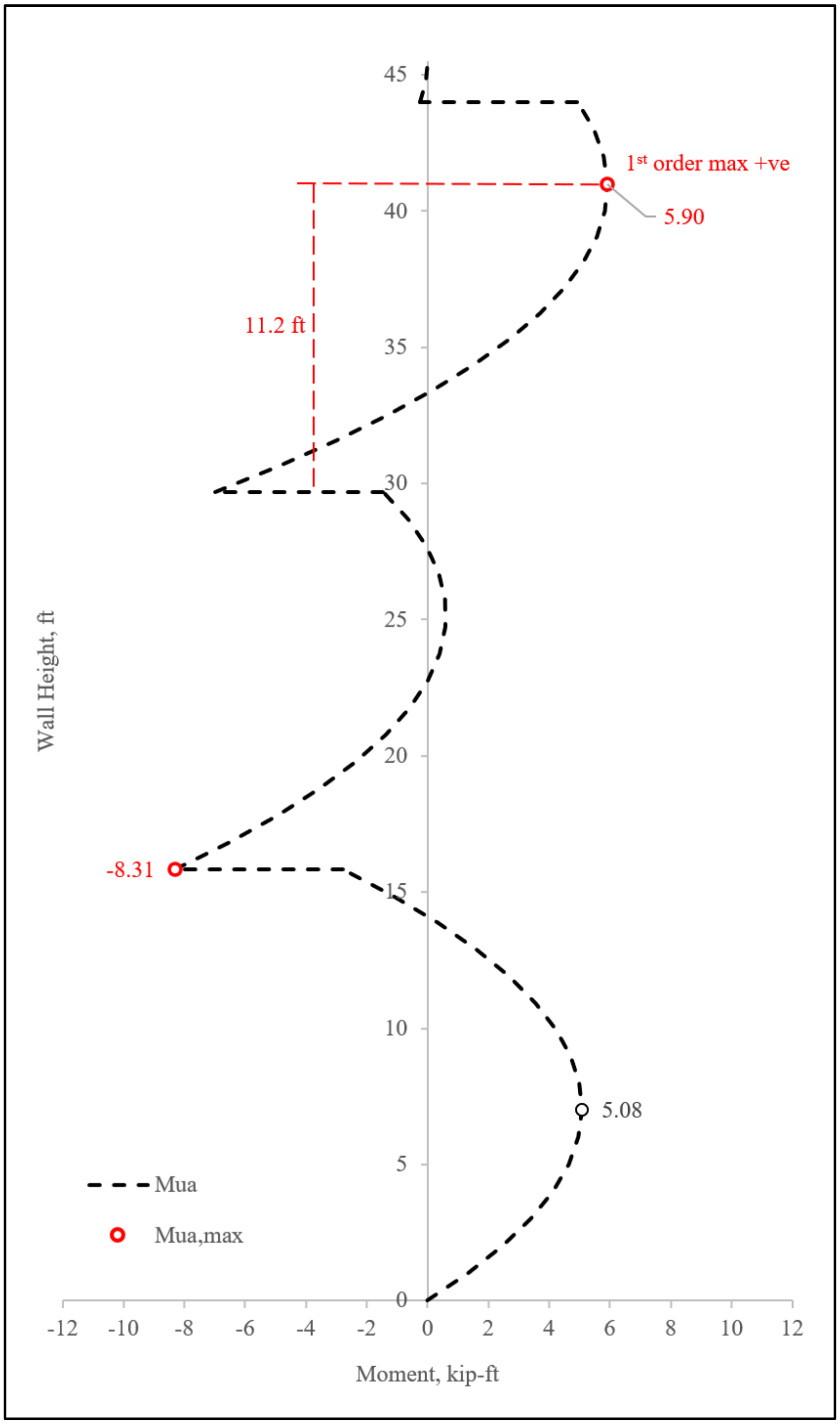


Figure 2 – First Order Moment Diagram for Load Combination 1 (Using Stiffness Method)

2.3. Wall Second Order Structural Analysis

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

$$P_{um} = 1.2\times(7.20+5.51)+1.6\times 7.50 = 27.25 \text{ kip}$$

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

$$A_{se} = A_s + \frac{P_{um}\times h}{2\times f_y \times d} = 4.84 + \frac{27.25\times 6.25}{2\times 60\times(6.25/2)} = 5.29 \text{ in.}^2$$ ***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.

$$a = \frac{A_{se}\times f_y}{0.85\times f_c'\times b} = \frac{5.29\times 60}{0.85\times 4\times(15\times 12)} = 0.519 \text{ in.}$$

$$c = \frac{a}{\beta_1} = \frac{0.519}{0.85} = 0.611 \text{ in.}$$

$$\frac{c}{d} = \frac{0.611}{3.13} = 0.195 < 0.375 \therefore \text{ tension-controlled}$$ ***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)***

$$I_{cr} = 8.0\times 5.29\times(3.13-0.611)^2 + \frac{(15\times 12)\times 0.611^3}{3} = 282.91 \text{ in.}^4$$ ***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 first order 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)***

$$K_b = \frac{48\times E_c\times I_{cr}}{5\times l_c^2} = \frac{48\times 3605\times 282.91}{5\times(14.3\times 12)^2} = 332.50 \text{ kip}$$

$$M_u = \frac{5.90}{1-\dfrac{27.25}{0.75\times 332.50}} = 6.62 \text{ ft-kip}$$

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

$$P_n = \frac{P_{um}}{\phi} = \frac{27.25}{0.9} = 30.28 \text{ kips}$$

$$a = \frac{A_{se,w}\times f_y}{0.85\times f_c'\times l_w} = \frac{\dfrac{P_n\times h}{2\times d}+A_s\times f_y}{0.85\times f_c'\times l_w} = \frac{\dfrac{30.28\times 6.25}{2\times 3.13}+4.84\times 60}{0.85\times 4\times 15\times 12} = 0.524 \text{ in.}$$

$$c = \frac{a}{\beta_1} = \frac{0.524}{0.85} = 0.616 \text{ in.}$$

$$\varepsilon_t = \left(\frac{0.003}{c}\right)\times d_t - 0.003 = \left(\frac{0.003}{0.616}\right)\times 3.13 - 0.003 = 0.0124 > 0.0050$$

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

3. Tilt-Up Wall Flexural Strength

According to ACI 318-14 (11.8.1.1(c)), the reinforcement shall provide design capacity greater than cracking capacity.

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}

$$f_r = 7.5\lambda\sqrt{f_c'} = 7.5\times 1.0\times\sqrt{4,000} = 474.34 \text{ psi}$$ **ACI 318-14 (19.2.3.1)**

$$I_g = \frac{l_w h^3}{12} = \frac{(15\times 12)\times 6.25^3}{12} = 3662.11 \text{ in.}^4$$

$$y_t = \frac{h}{2} = \frac{6.25}{2} = 3.13 \text{ in.}$$

$$M_{cr} = \frac{f_r I_g}{y_t} = \frac{474.34\times 3662.11}{3.13}\times\frac{1}{1000}\times\frac{1}{12} = 46.32 \text{ ft-kip}$$ **ACI 318-14 (24.2.3.5(b))**

3.2. Wall Flexural Moment Capacity (ϕM_n)

For load combination #1:

$$M_n = A_{se}\times f_y\times\left(d-\frac{a}{2}\right) = 5.29\times 60\times\left(3.13-\frac{0.519}{2}\right) = 75.85 \text{ ft-kip}$$

It was shown previously that the section is tension controlled → $\phi = 0.9$

$$\phi M_n = \phi \times M_n = 0.9 \times 75.85 = 68.27 \text{ ft-kip} > M_u = 6.62 \text{ ft-kip} \ (\textbf{o.k.})$$ **ACI 318-14 (11.5.1.1(b))**

$$\phi M_n = 68.27 \text{ ft-kip} > M_{cr} = 46.32 \text{ ft-kip} \ (\textbf{o.k.})$$ **ACI 318-14 (11.8.1.1(c))**

$$\Delta_u = \frac{M_u}{0.75 \times K_b} = \frac{6.62 \times 12}{0.75 \times 332.50} = 0.319 \text{ in.}$$ **ACI 318-14 (11.8.3.1(b))**

The same procedure was repeated for positive moment section at 7 ft height and negative moment section at 15.83 ft height (see the following table).

Table 1 – Multi-Story Panel Hand Solution Results at Critical Sections

Location	M_{ua} (kip-ft)	M_u (kip-ft)	Magnifier	$D_{z,ultimate}$ (in.)
y = 7 ft (Span 1)	+5.08	+8.54	1.681*	0.354
y = 40.86 ft (Span 3)	+5.90	+6.62	1.123	0.319
y = 15.83 ft(Span 2)	-8.31	-9.33*	1.123	0.000

* the magnifier for span 1 exceeds the limit established in ACI 318-14 6.2.6 (1.68 > 1.40) and should be investigated further

3.3. Tilt-Up Wall Flexural Reinforcement

At the maximum positive moment location in span 3, I_{cr} equals 282.91 in.^{4} corresponding to 11 #6 bars. At this location, the wall capacity far exceeds the maximum moment (ϕM_n = 68.27 ft-kip >> M_u = 6.62 ft-kip), the corresponding cracking coefficient ($0.75I_{cr}/I_g$) = 0.05794. 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 A_s, a lower value may be possibly obtained for strength calculations using 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 Axial Strength Check

$$\frac{P_{um}}{A_g} = \frac{27.25 \times 1000}{6.25 \times (15 \times 12)} = 24.22 \text{ psi} < 0.06 \times f'_c = 0.06 \times 4{,}000 = 240 \text{ psi} \ (\textbf{o.k.})$$ **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 56 kips and no detailed calculations are required by engineering judgement. See figure 12a, 12b, and 12c for detailed shear force, in-plane shear strength, and out of plane shear strength diagrams.

6. Tilt-Up Wall Panel 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 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 wall reinforcement. In stiffeners and boundary elements, spWall calculates the required shear and torsion steel reinforcement. Wall concrete shear 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 tilt-up 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: $1.2D + 1.6L_r + 0.5W$

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

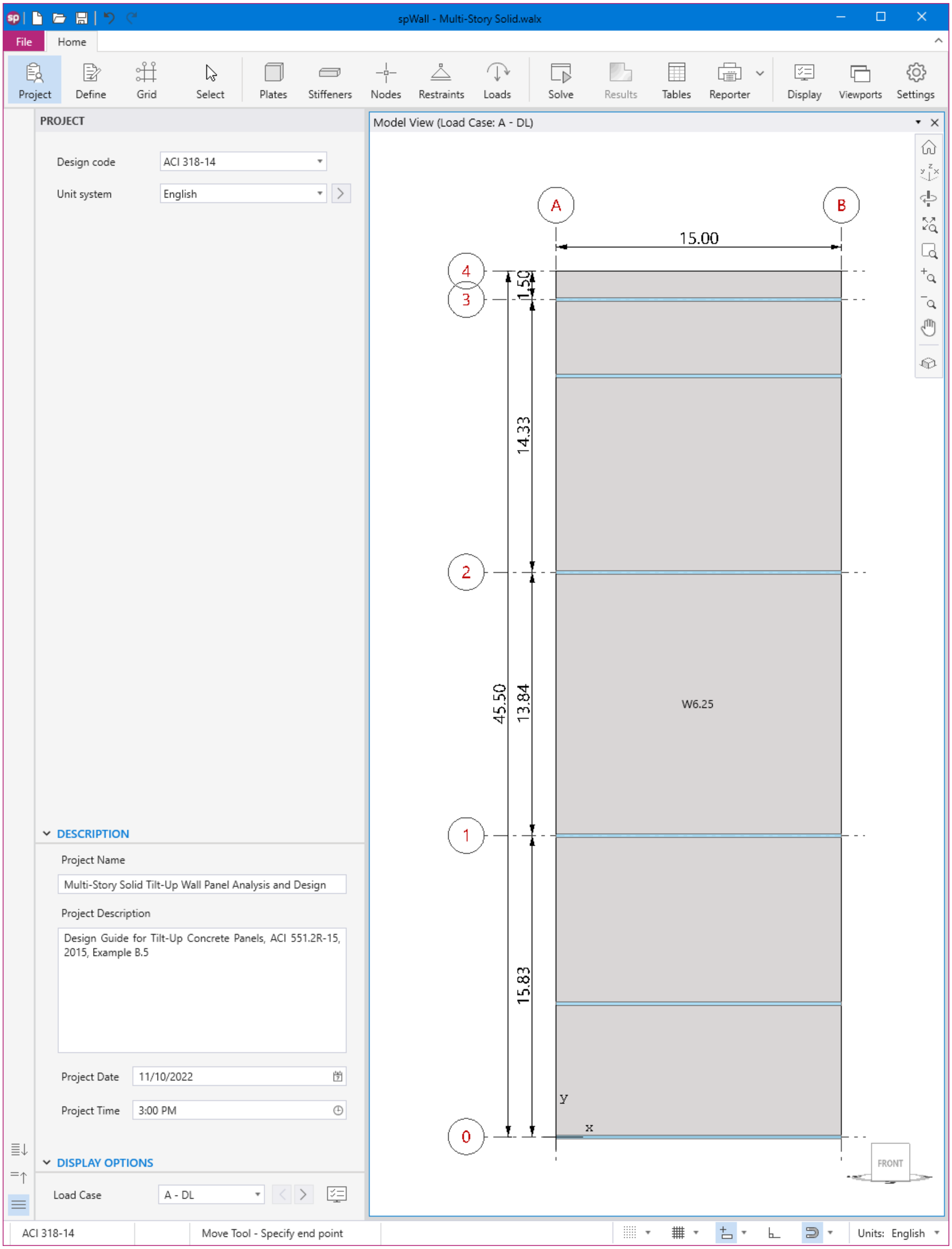


Figure 3 – spWall Interface

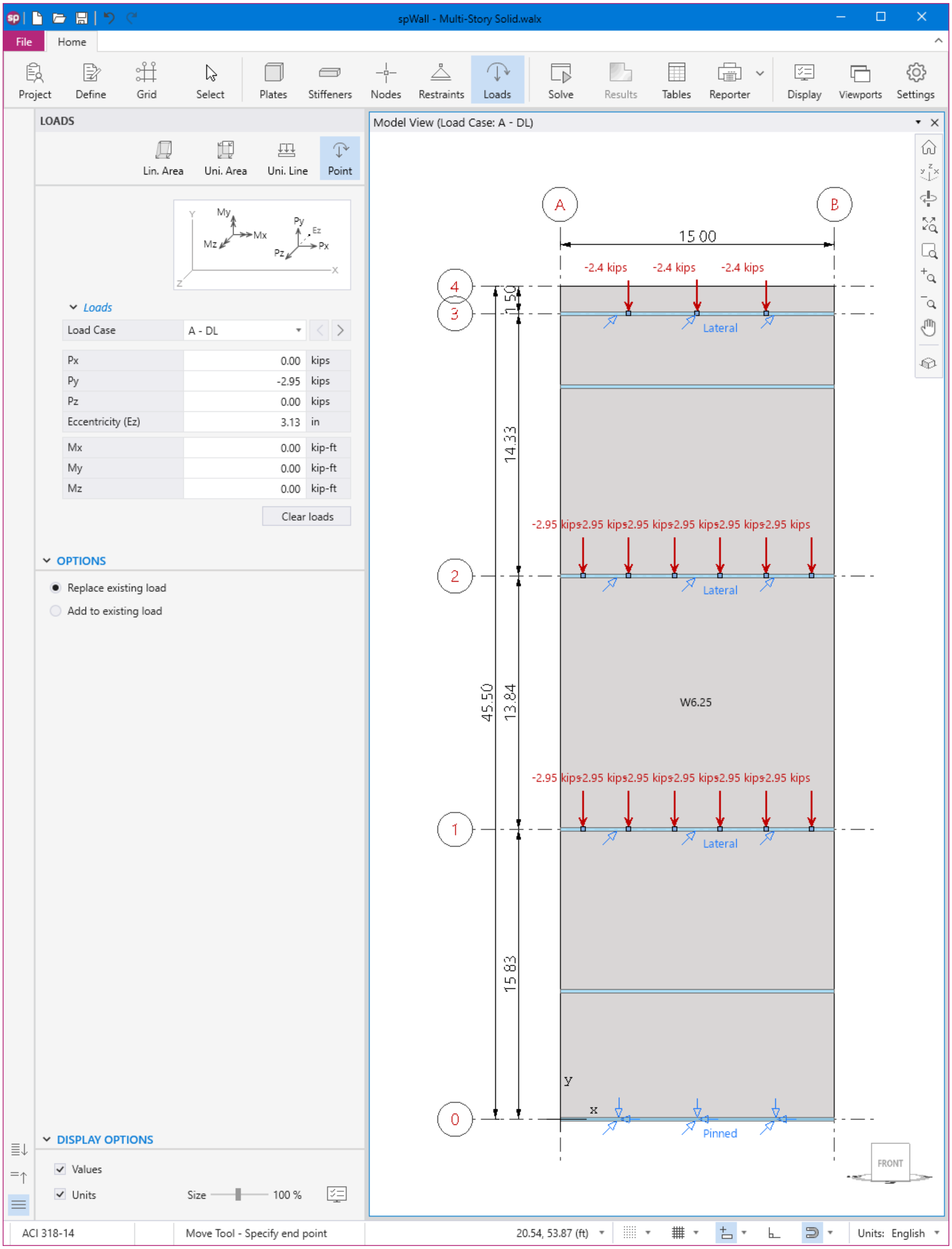


Figure 4 – Assigning Dead Loads for Multi-Story Tilt-Up Wall Panel (spWall)

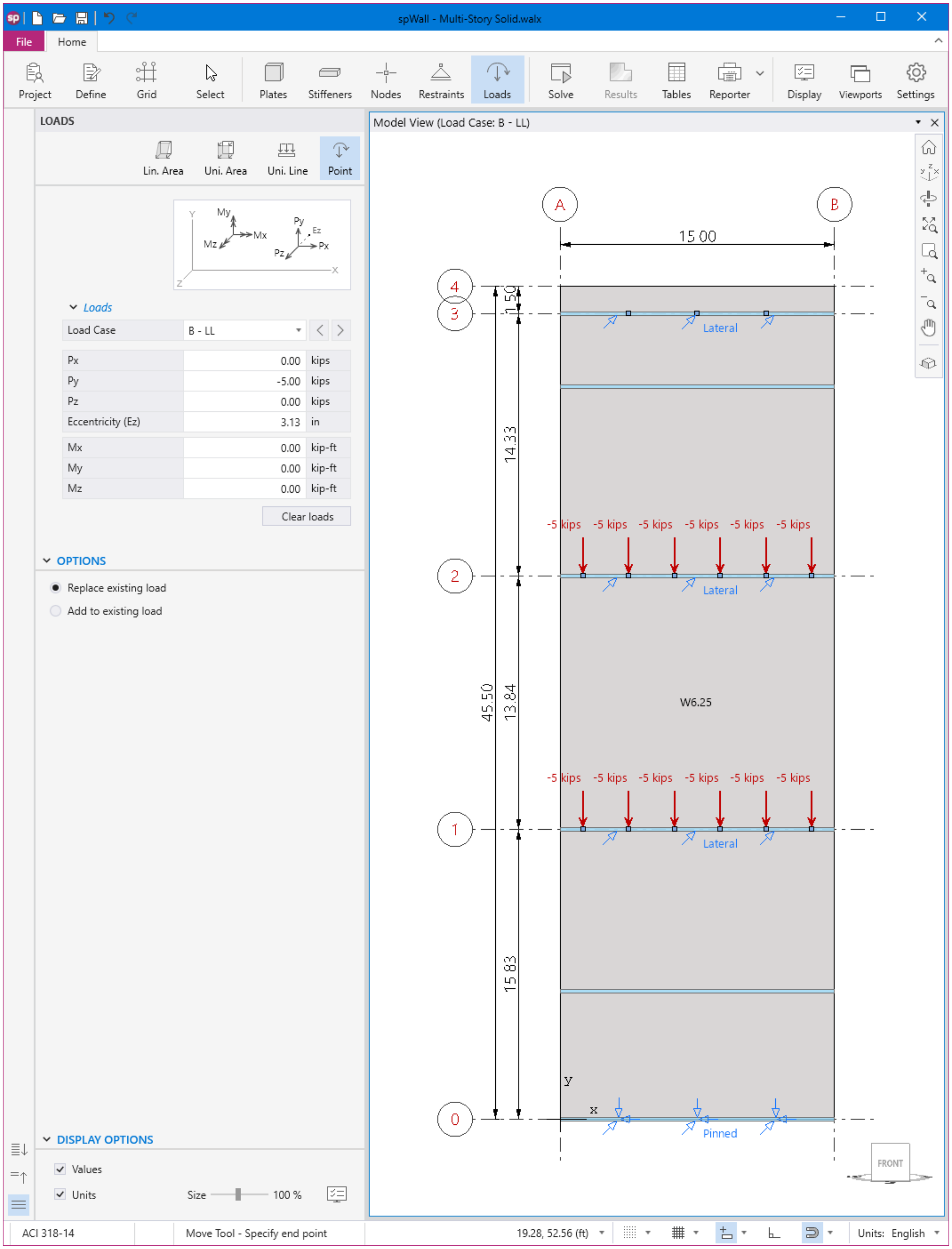


Figure 5 – Assigning Live Loads for Multi-Story Tilt-Up Wall Panel (spWall)

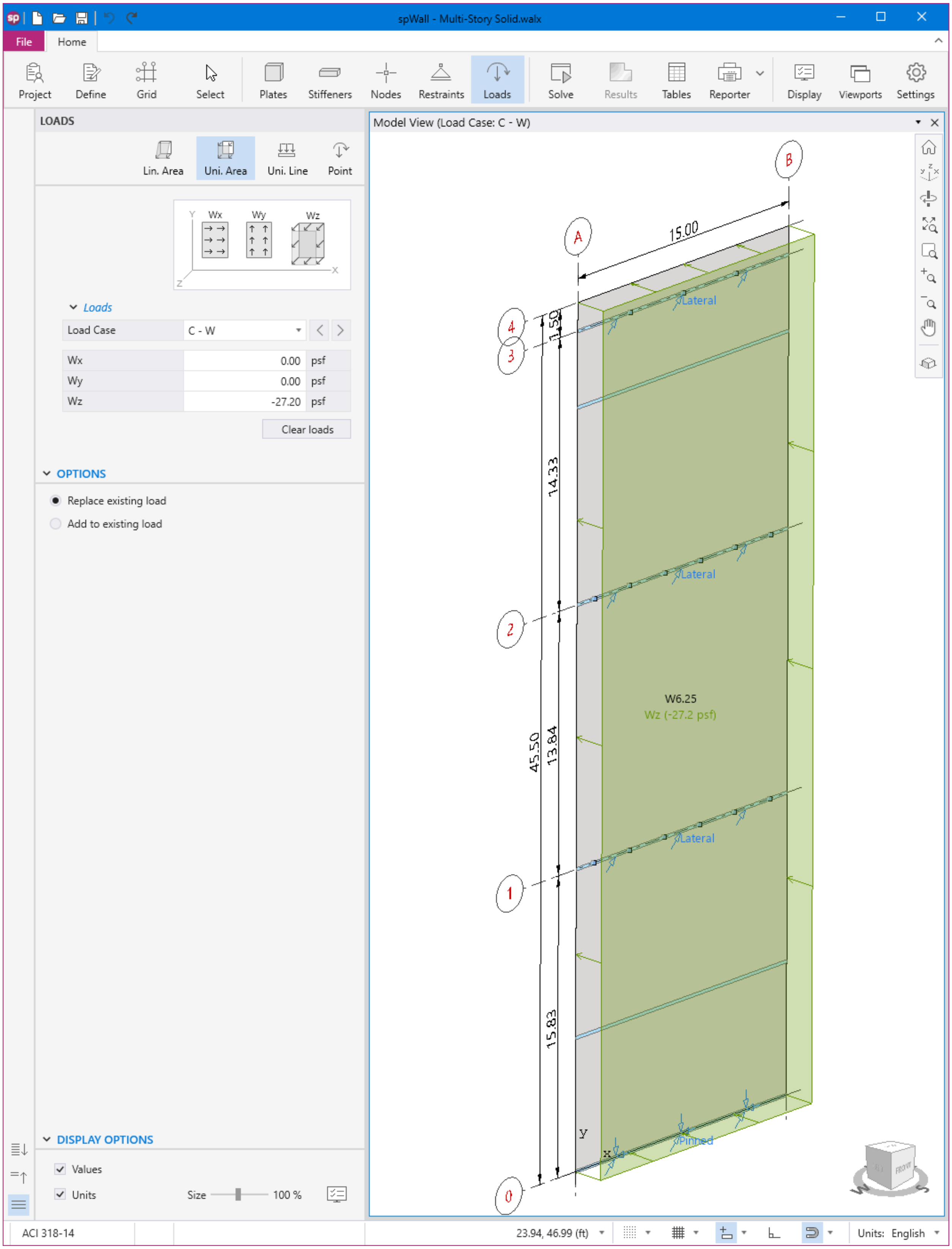


Figure 6 – Assigning Wind Loads for Multi-Story Tilt-Up Wall Panel (spWall)

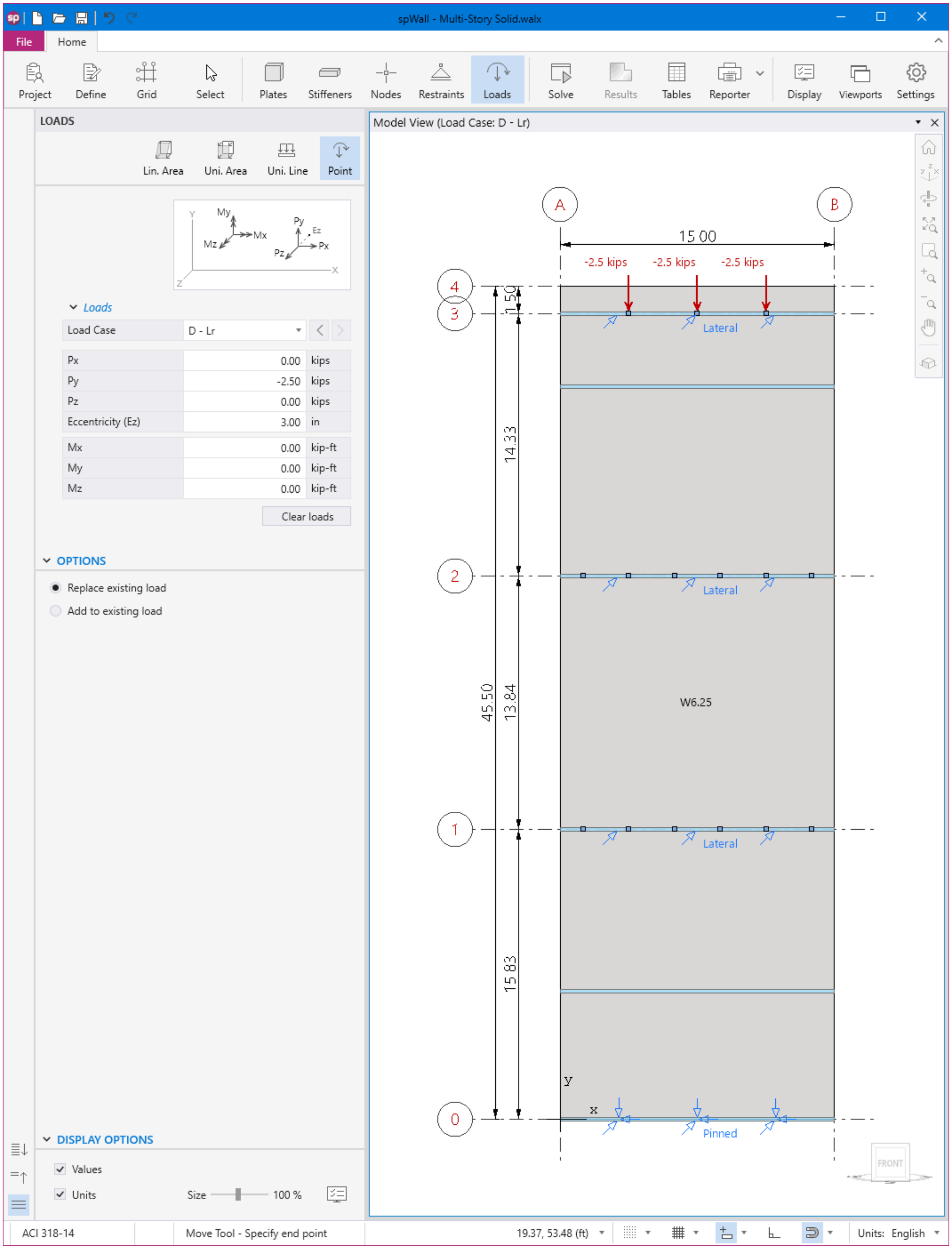


Figure 7 – Assigning Roof Live Loads for Multi-Story Tilt-Up Wall Panel (spWall)

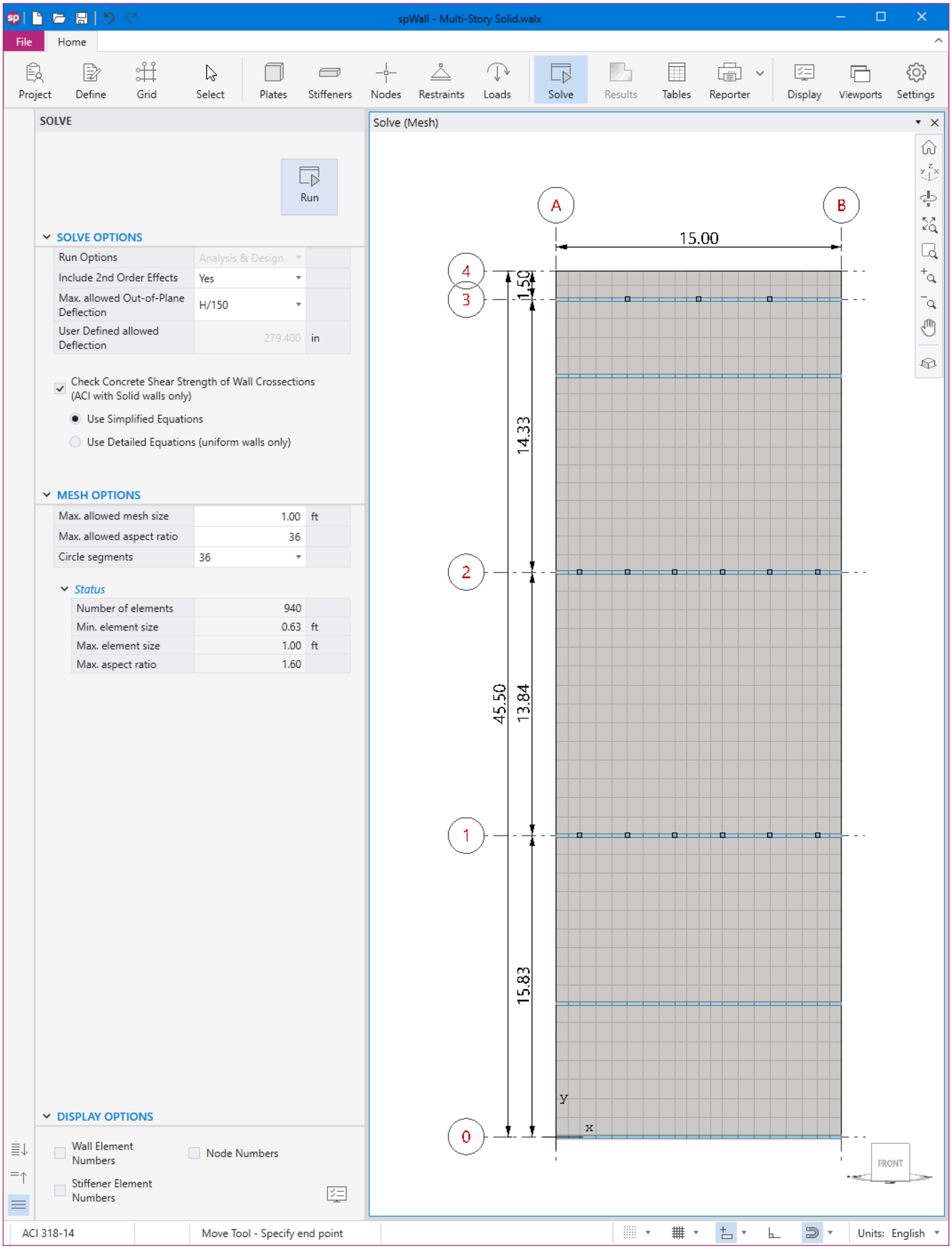


Figure 8 – Solve and Mesh Options (spWall)

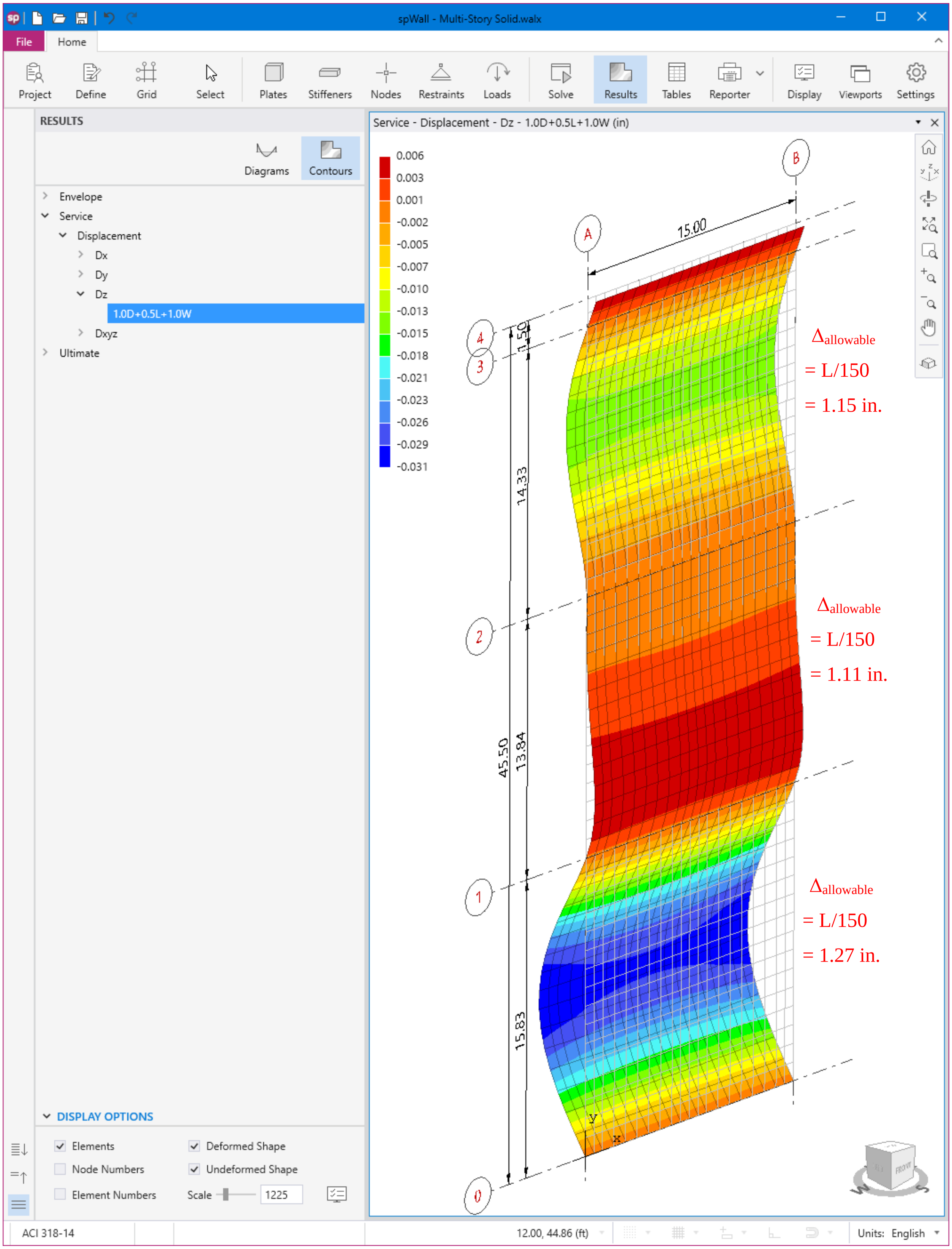


Figure 9 – Multi-Story Tilt-Up Wall Panel Service Displacements (spWall)

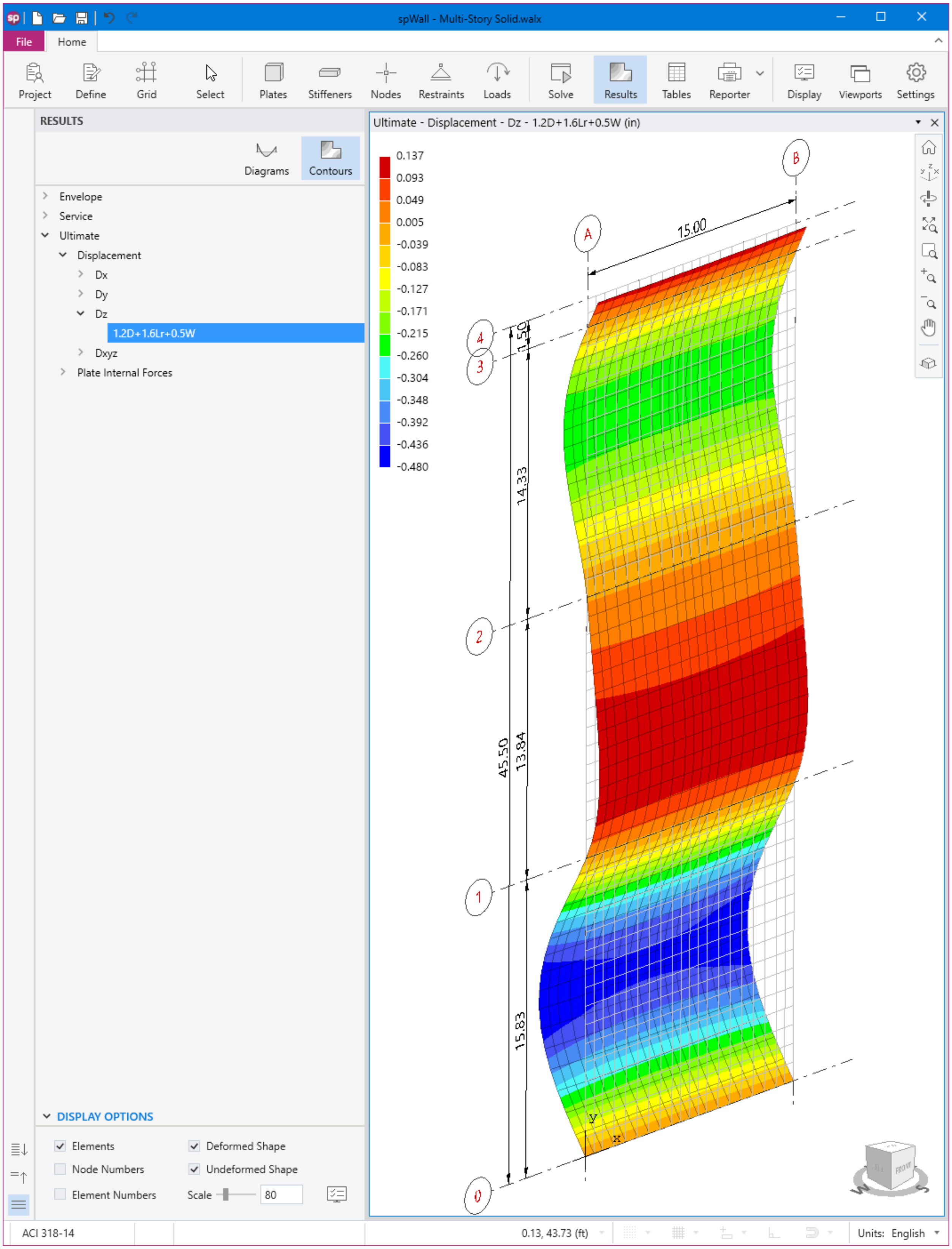


Figure 10 – Multi-Story Tilt-Up Wall Panel Ultimate Displacements (spWall)

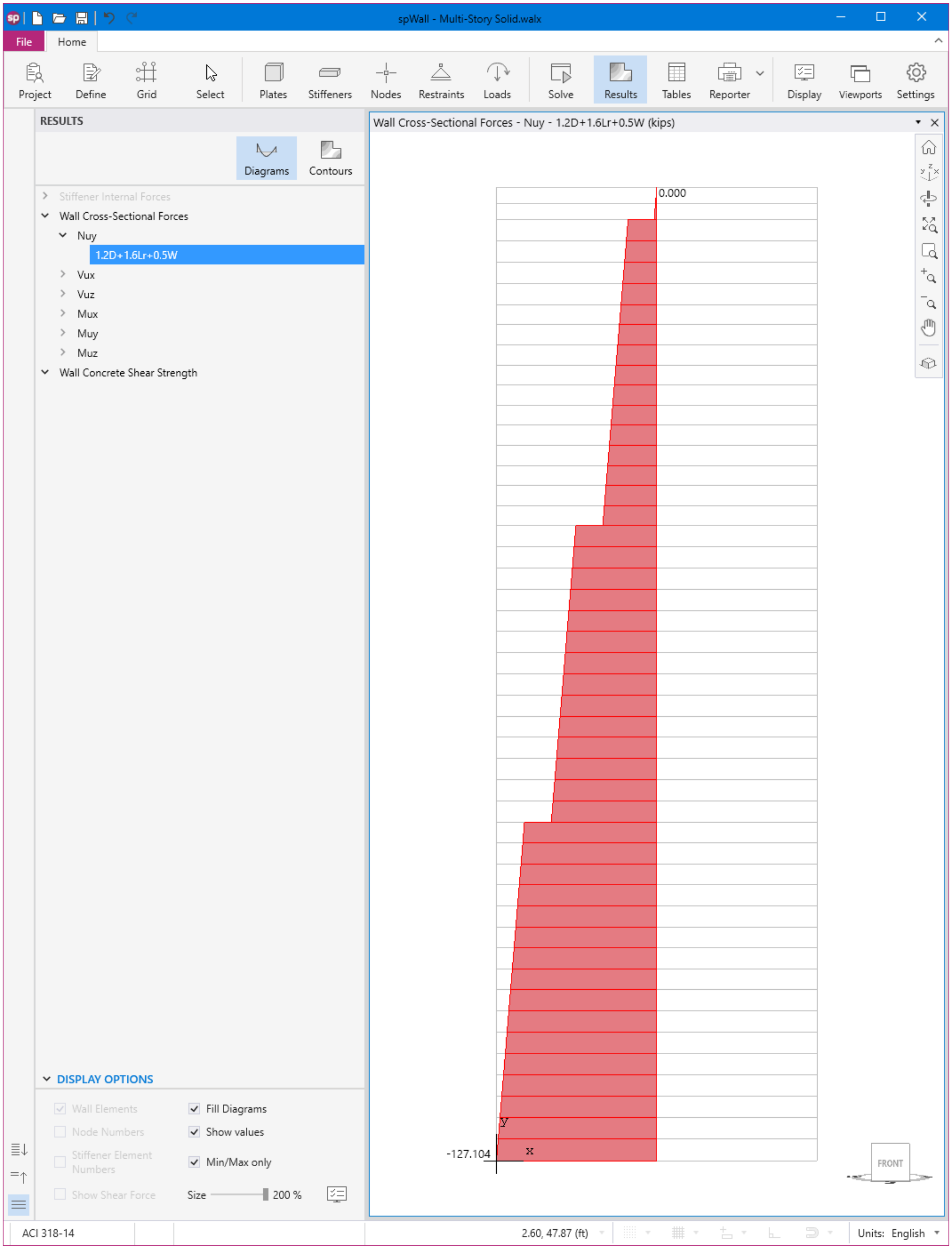


Figure 11 – Multi-Story Tilt-Up Wall Panel Axial Force Diagram (spWall)

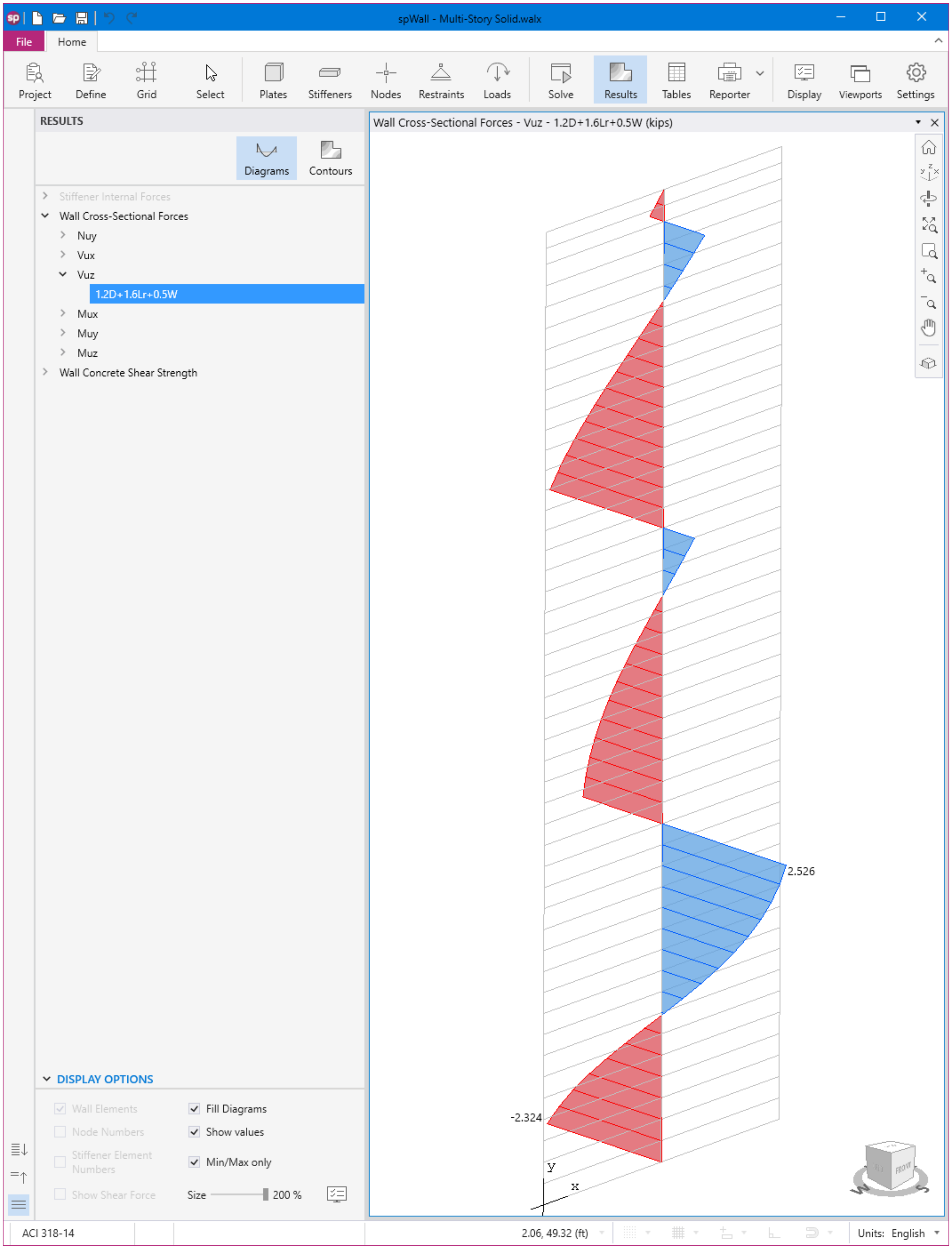


Figure 12a – Out-of-Plane Shear Force Diagram (spWall)

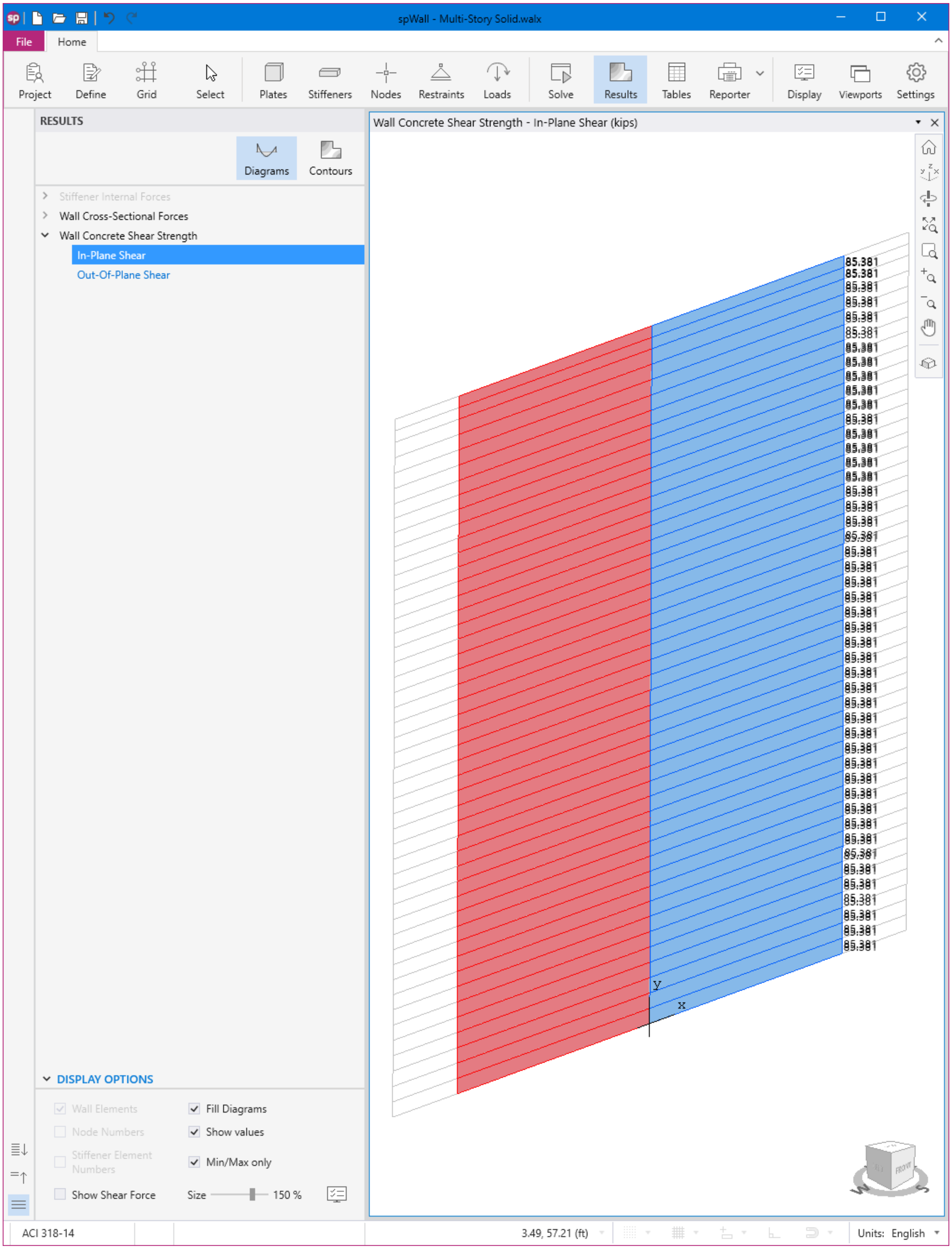


Figure 12b – In-Plane Shear Force Diagram (spWall)

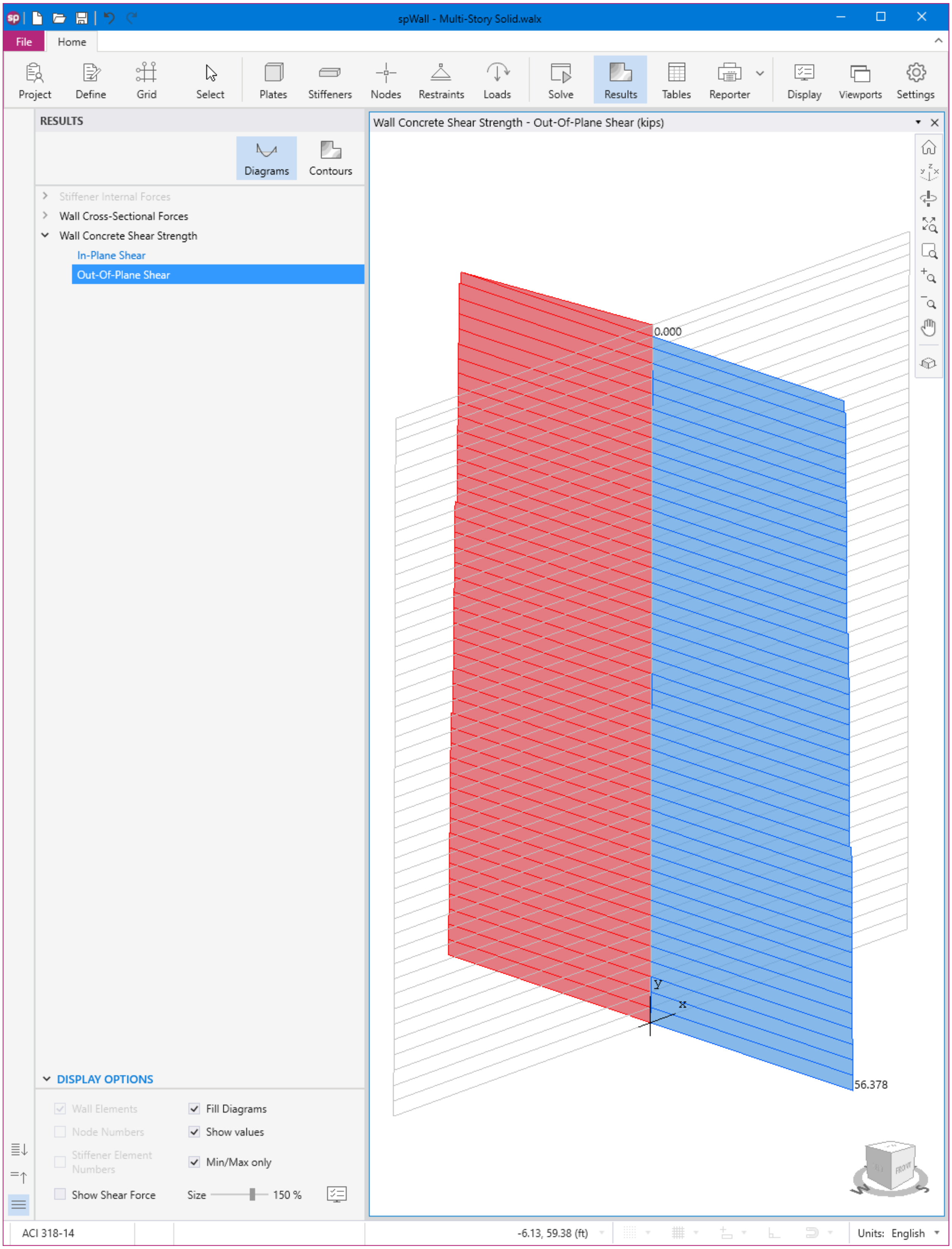


Figure 12c – Out-of-Plane Shear Force Diagram (spWall)

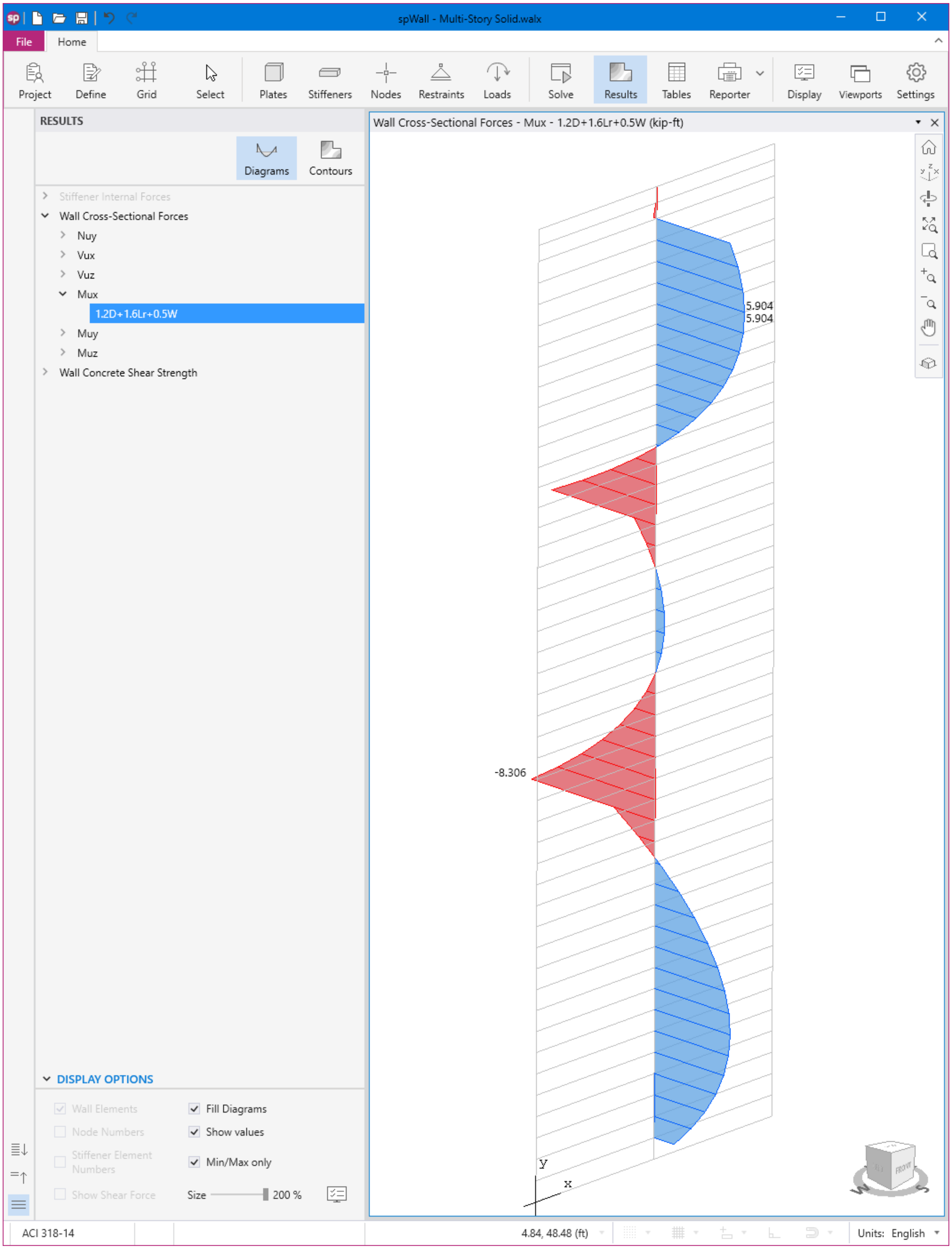


Figure 13 – Multi-Story Tilt-Up Wall First Order Moment (M_{ua}) Diagram (spWall)

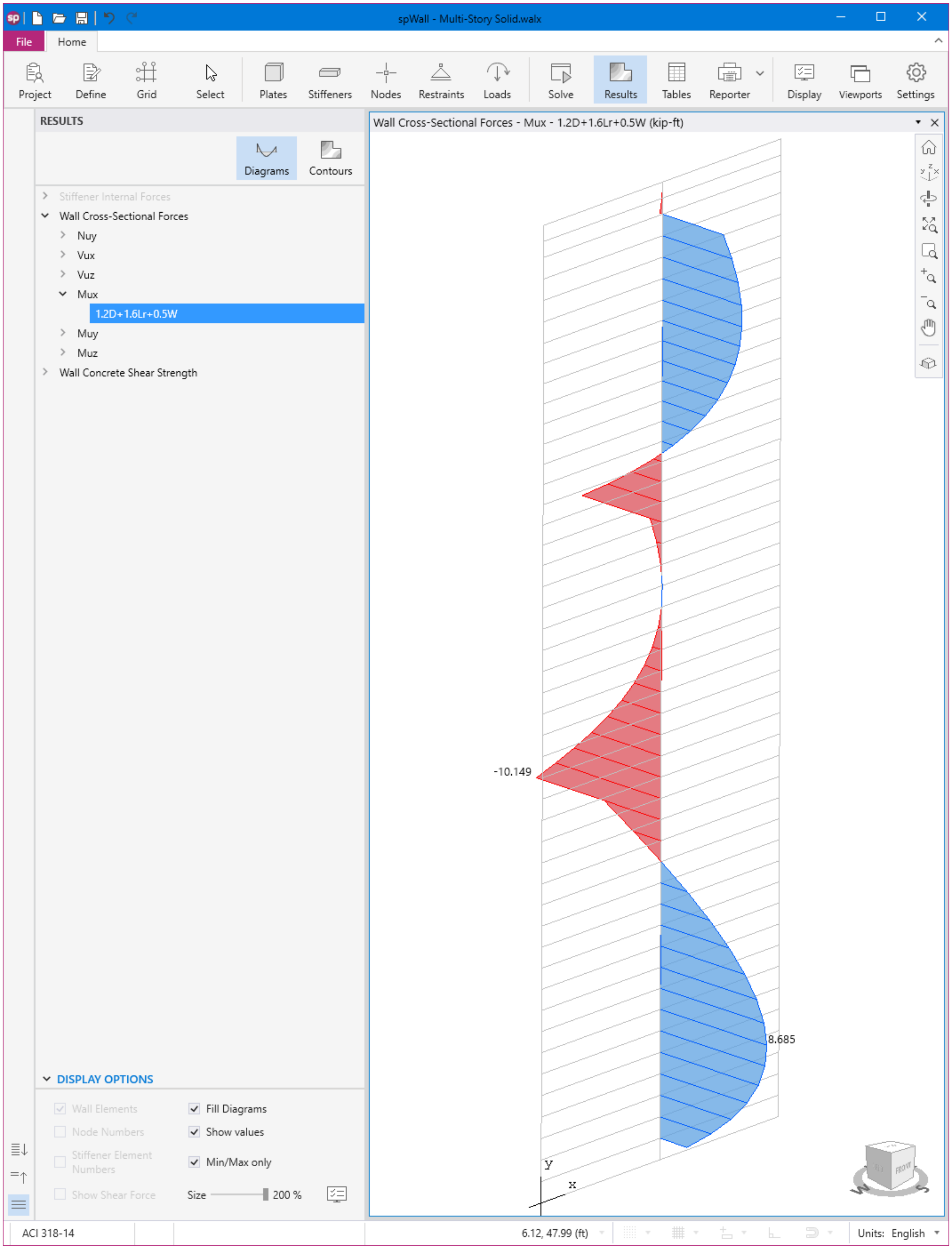


Figure 14 – Multi-Story Tilt-Up Wall Second Order Moment (M_u) Diagram (spWall)

1. Results

1.1. Ultimate

1.1.1. Nodal Displacements

1.1.1.1. 1.2D+1.6Lr+0.5W

Coordinate System: Global

Node	Dx in	Dy in	Dz in
148	-0.001	-0.003	-0.287
149	0.000	-0.003	-0.282
150	0.000	-0.003	-0.278
151	0.000	-0.003	-0.274
152	0.000	-0.003	-0.271
153	0.000	-0.002	-0.268
154	0.000	-0.002	-0.267
155	0.000	-0.002	-0.266
156	0.000	-0.002	-0.265
157	0.000	-0.002	-0.264
158	0.000	-0.002	-0.264
159	0.000	-0.002	-0.264
160	0.000	-0.002	-0.265
161	0.000	-0.002	-0.266
162	0.000	-0.002	-0.267
163	0.000	-0.002	-0.268
164	0.000	-0.003	-0.271
165	0.000	-0.003	-0.274
166	0.000	-0.003	-0.278
167	0.000	-0.003	-0.282
168	0.001	-0.003	-0.287

$D_{z,averaged}$ @ 7 ft = 0.272 in.

337	0.000	-0.005	0.000
338	0.000	-0.005	0.000
339	0.000	-0.005	0.000
340	0.000	-0.005	0.000
341	0.000	-0.005	0.000
342	0.000	-0.005	0.000
343	0.000	-0.005	0.000
344	0.000	-0.005	0.000
345	0.000	-0.005	0.000
346	0.000	-0.005	0.000
347	0.000	-0.005	0.000
348	0.000	-0.005	0.000
349	0.000	-0.005	0.000
350	0.000	-0.005	0.000
351	0.000	-0.005	0.000
352	0.000	-0.005	0.000
353	0.000	-0.005	0.000
354	0.000	-0.005	0.000
355	0.000	-0.005	0.000
356	0.000	-0.005	0.000
357	0.000	-0.005	0.000

$D_{z,averaged}$ @ 15.83 ft = 0.000 in.

Node	Dx	Dy	Dz
	in	in	in
883	0.000	-0.009	-0.155
884	0.000	-0.009	-0.153
885	0.000	-0.009	-0.153
886	0.000	-0.010	-0.153
887	0.000	-0.010	-0.154
888	0.000	-0.010	-0.156
889	0.000	-0.010	-0.157
890	0.000	-0.010	-0.157
891	0.000	-0.010	-0.158
892	0.000	-0.010	-0.158
893	0.000	-0.010	-0.159
894	0.000	-0.010	-0.158
895	0.000	-0.010	-0.158
896	0.000	-0.010	-0.157
897	0.000	-0.010	-0.157
898	0.000	-0.010	-0.156
899	0.000	-0.010	-0.154
900	0.000	-0.010	-0.153
901	0.000	-0.009	-0.153
902	0.000	-0.009	-0.153
903	0.000	-0.009	-0.155

$D_{z,averaged}$ @ 41 ft = 0.156 in.

Figure 15 – Ultimate Displacement at Critical Sections (First Order Analysis) (spWall)

1.1.2. Wall Cross-Sectional Forces

1.1.2.1. 1.2D+1.6Lr+0.5W

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
8-	7.00	7.50	0.00	-117.26	0.00	-0.01	5.08	0.00
8+	7.00	7.50	0.00	-117.26	0.00	-0.01	5.08	0.00
17+	15.83	7.50	0.00	-83.60	0.00	-1.91	-8.31	0.00
43-	41.00	7.50	0.00	-26.97	0.00	0.02	5.90	0.00
43+	41.00	7.50	0.00	-26.97	0.00	0.02	5.90	0.00

Figure 16 – Multi-Story Tilt-Up Wall Panel Cross-Sectional Forces (First Order Analysis) (spWall)

1. Results

1.1. Ultimate

1.1.1. Nodal Displacements

1.1.1.1. 1.2D+1.6Lr+0.5W

Coordinate System: Global

Node	Dx	Dy	Dz
	in	in	in
148	-0.001	-0.003	-0.480
149	0.000	-0.003	-0.472
150	0.000	-0.003	-0.465
151	0.000	-0.003	-0.458
152	0.000	-0.003	-0.453
153	0.000	-0.002	-0.449
154	0.000	-0.002	-0.446
155	0.000	-0.002	-0.444
156	0.000	-0.002	-0.443
157	0.000	-0.002	-0.442
158	0.000	-0.002	-0.442
159	0.000	-0.002	-0.442
160	0.000	-0.002	-0.443
161	0.000	-0.002	-0.444
162	0.000	-0.002	-0.446
163	0.000	-0.002	-0.449
164	0.000	-0.003	-0.453
165	0.000	-0.003	-0.458
166	0.000	-0.003	-0.465
167	0.000	-0.003	-0.472
168	0.001	-0.003	-0.480
337	0.000	-0.005	0.000
338	0.000	-0.005	0.000
339	0.000	-0.005	0.000
340	0.000	-0.005	0.000
341	0.000	-0.005	0.000
342	0.000	-0.005	0.000
343	0.000	-0.005	0.000
344	0.000	-0.005	0.000
345	0.000	-0.005	0.000
346	0.000	-0.005	0.000
347	0.000	-0.005	0.000
348	0.000	-0.005	0.000
349	0.000	-0.005	0.000
350	0.000	-0.005	0.000
351	0.000	-0.005	0.000
352	0.000	-0.005	0.000
353	0.000	-0.005	0.000
354	0.000	-0.005	0.000
355	0.000	-0.005	0.000
356	0.000	-0.005	0.000
357	0.000	-0.005	0.000

$D_{z,averaged}$ @ 7 ft = 0.455 in.

$D_{z,averaged}$ @ 15.83 ft = 0.000 in.

Node	Dx	Dy	Dz
	in	in	in
862	0.000	-0.009	-0.217
863	0.000	-0.009	-0.214
864	0.000	-0.009	-0.213
865	0.000	-0.009	-0.212
866	0.000	-0.010	-0.213
867	0.000	-0.010	-0.213
868	0.000	-0.010	-0.214
869	0.000	-0.010	-0.215
870	0.000	-0.010	-0.215
871	0.000	-0.010	-0.216
872	0.000	-0.010	-0.216
873	0.000	-0.010	-0.216
874	0.000	-0.010	-0.215
875	0.000	-0.010	-0.215
876	0.000	-0.010	-0.214
877	0.000	-0.010	-0.213
878	0.000	-0.010	-0.213
879	0.000	-0.009	-0.212
880	0.000	-0.009	-0.213
881	0.000	-0.009	-0.214
882	0.000	-0.009	-0.217

$D_{z,averaged}$ @ 40 ft = 0.214 in.

Figure 17 – Ultimate Displacement at Critical Sections (Second Order Analysis) (spWall)

1.1.2. Wall Cross-Sectional Forces

1.1.2.1. 1.2D+1.6Lr+0.5W

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
8-	7.00	7.50	0.00	-117.26	0.00	0.05	8.68	0.00
8+	7.00	7.50	0.00	-117.26	0.00	0.05	8.68	0.00
17+	15.83	7.50	0.00	-83.60	0.00	-1.62	-10.15	0.00
42-	40.00	7.50	0.00	-28.37	0.00	-0.07	6.48	0.00
42+	40.00	7.50	0.00	-28.37	0.00	-0.07	6.48	0.00

Figure 18 – Multi-Story Tilt-Up Wall Panel Cross-Sectional Forces (Second Order Analysis) (spWall)

7. Design Results Comparison and Conclusions

Table 2 – Comparison of Multi-Story Panel Analysis Results					
Moment	Location	Solution	M_{ua} (kip-ft)	M_u (kip-ft)	$D_{z,ultimate}$ (in.)
Max Positive	y = 7 ft (Span 1)	Hand	5.08	8.54	0.354
		spWall	5.08	8.68	0.455
	y = 40 ft (Span 3)	Hand	5.90	6.62**	0.319**
		spWall	5.90	6.48	0.214
Max Negative	y = 15.83 ft (Span 2)	Hand	-8.31	-9.33*	0.000
		spWall	-8.31	-10.15	0.000

* Reference incorrectly used the same moment magnification factor for the maximum positive and negative sections. Refer to the following section for a detailed discussion.

** Reference incorrectly obtained the maximum positive second order moment assuming the maximum second order moment will occur at the same location. Refer to the following section for a detailed discussion.

The results of all the hand calculations as illustrated above are generally in good agreement with the automated results obtained from the spWall FEA. Detailed commentary on the exceptions in this comparison is provided in the following section.

8. 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))***
- The concentrated loads application limits shall be met — ***ACI 318-14 (11.8.2.2)***
- 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(e))***

For multi-story panels, ACI 551 utilized the alternative analysis method even though some of the conditions above are not met. The comparison shown previously identified two important issues summarized in this section along with StructurePoint's observations and recommendations.

Issue #1: **Proper calculation of moment magnification**

Using the same moment magnification factor (magnifier) for the maximum negative moment section based on the properties of the maximum positive moment section within the same span is not valid. In some cases, this will underestimate the second order design moment at the negative section.

Recommendation: Calculate the moment magnification factor separately for positive and negative moments and repeat for each wall segment or conservatively use the highest magnification factor. This procedure should be repeated for all load combinations under consideration.

Illustration: In this Example, this issue is illustrated in Figures 19 and 20 for Load Combination 1 ($1.2D + 1.6L_r + 0.5W$) where:

Current Procedure: $M_{u,negative}$ = -9.33 kip-ft (Using positive moment magnification factor from span 3).

Recommended Procedure: $M_{u,negative}$ = -13.73 kip-ft (Using the correct negative moment magnification factor from span 1 where the max negative moment occurs, see the following table).

Issue #2: **Proper location of maximum design moments**

For multi-story tilt-up panels such as the panel discussed in this Example, the location of maximum positive and negative moment can vary between first and second order analyses. Thus, locating and magnifying the maximum moment based on first order analysis to estimate the maximum second order moment may be incorrect for some cases. This can lead to underestimating maximum moments and deflections as shown in Figure 20.

Recommendation: Perform the ACI 551 procedure for each wall span individually and evaluate maximum positive and negative design moment values separately after considering moment magnification due to second order effects.

Illustration: In this Example, this issue is illustrated for Load Combination 1 ($1.2D + 1.6L_r + 0.5W$) where in table 3 the maximum positive design moment moved to Span 1 after second order analysis (magnification) while the maximum negative design moment remained in span 1.

Table 3 - Comparison of Design Moments						
Method	Maximum Positive (issue 2)			Maximum Negative (issue 1)		
	M_{ua} kip-ft	M_u kip-ft	Location	M_{ua} kip-ft	M_u kip-ft	Location
Current Procedure	+5.90	+6.62	Span 3	-8.31	-9.33	Span 1
Recommended Procedure	+5.08	+10.05	***Span 1***	-8.31	-13.73	Span 1

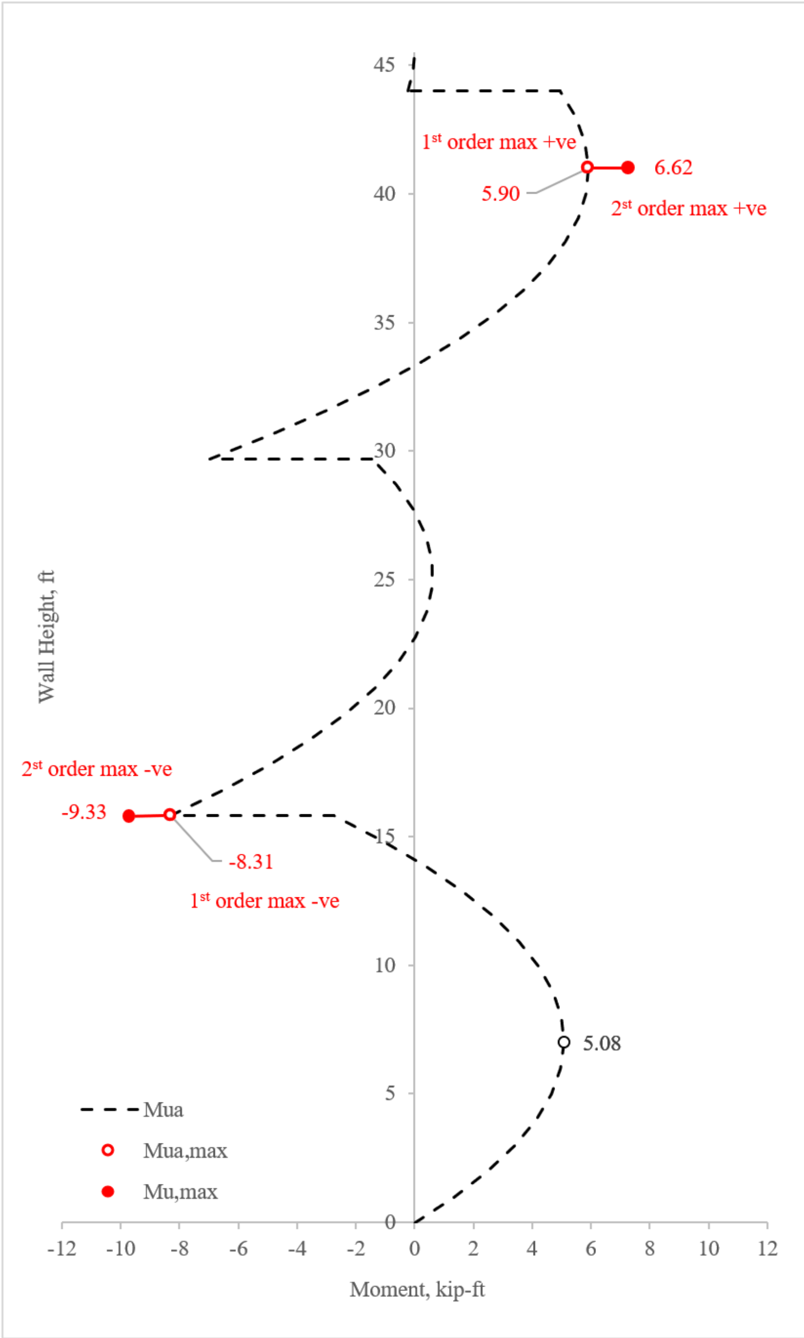


Figure 19 – First Order Moment Diagram and Second Order Maximum Moments (Current Procedure)

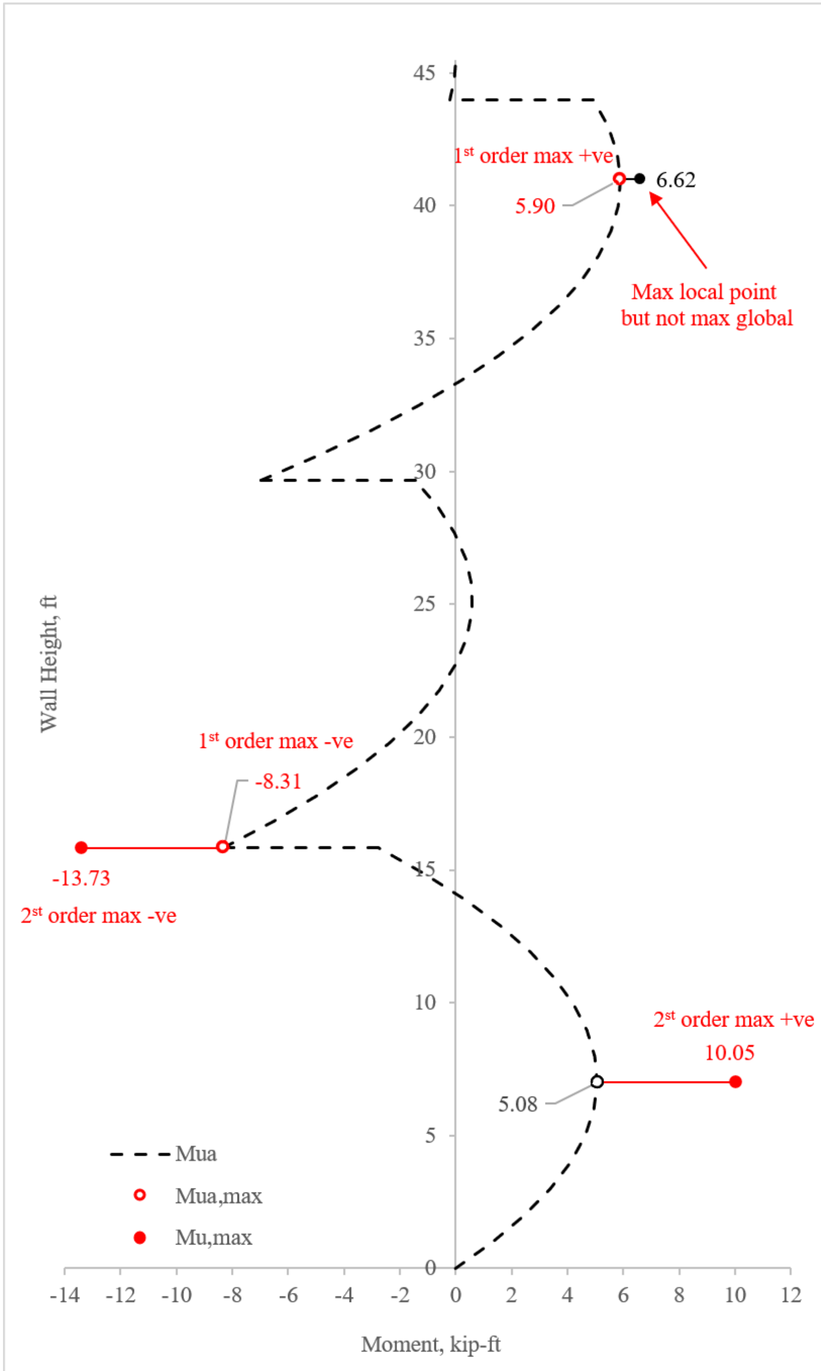


Figure 20 – First Order Moment Diagram and Second Order Maximum Moments (Recommended Procedure)

Conclusions and Observations

The information presented for first order and recommended second order moments has been verified using an FEA spWall model of the multi-story tilt-up wall panel as shown in the following figure.

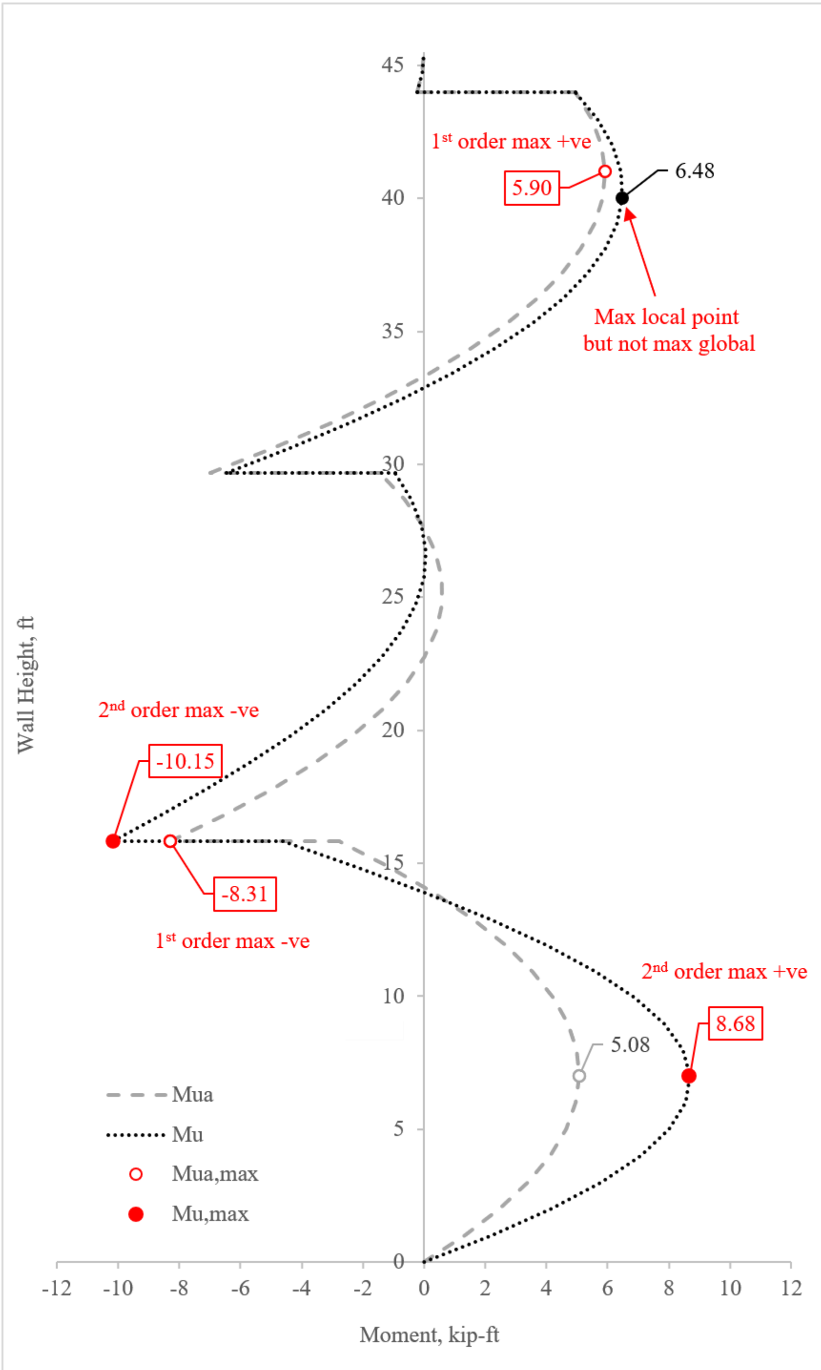


Figure 21 – First and Second Order Moment Diagrams (Using FEA - spWall)

The results indicate good agreement with the ACI 551 procedure when the recommended corrections are implemented. It is worth noting that the magnified positive and negative moments are slightly conservative in comparison with the corresponding FEA value as can be seen in the following table.

Table 4 - Comparison of Recommended Procedure with FEA (Bending Moments)								
Method	Maximum Positive				Maximum Negative			
	M_{ua} kip-ft	M_u kip-ft	Magnifier	Location	M_{ua} kip-ft	M_u kip-ft	Magnifier	Location
Recommended Procedure	+5.08	+10.05	1.98	Span 1	-8.31	-13.73	1.65	Span 1
FEA spWall	+5.08	+8.68	1.71	Span 1	-8.31	-10.15	1.22	Span 1

Table 5 - Comparison of Recommended Procedure with FEA (Axial Forces)			
Method	P_{um}, kip		
	y = 7 ft (Span 1)	y = 15.83 ft (Span 2)	y = 40.86 ft (Span 3)
Recommended Procedure	117.26	104.84	27.25
FEA spWall	117.26	104.84	27.17

Table 6 - Comparison of Recommended Procedure with FEA (Out-of-Plane Shear Forces)						
Method	V_u, kip			ϕV_c, kip		
	y = 7 ft	y = 15.83 ft	y = 40.86 ft	y = 7 ft	y = 15.83 ft	y = 40.86 ft
Recommended Procedure	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.
FEA spWall	0.05	2.53	0.13	56.14	55.85	54.01