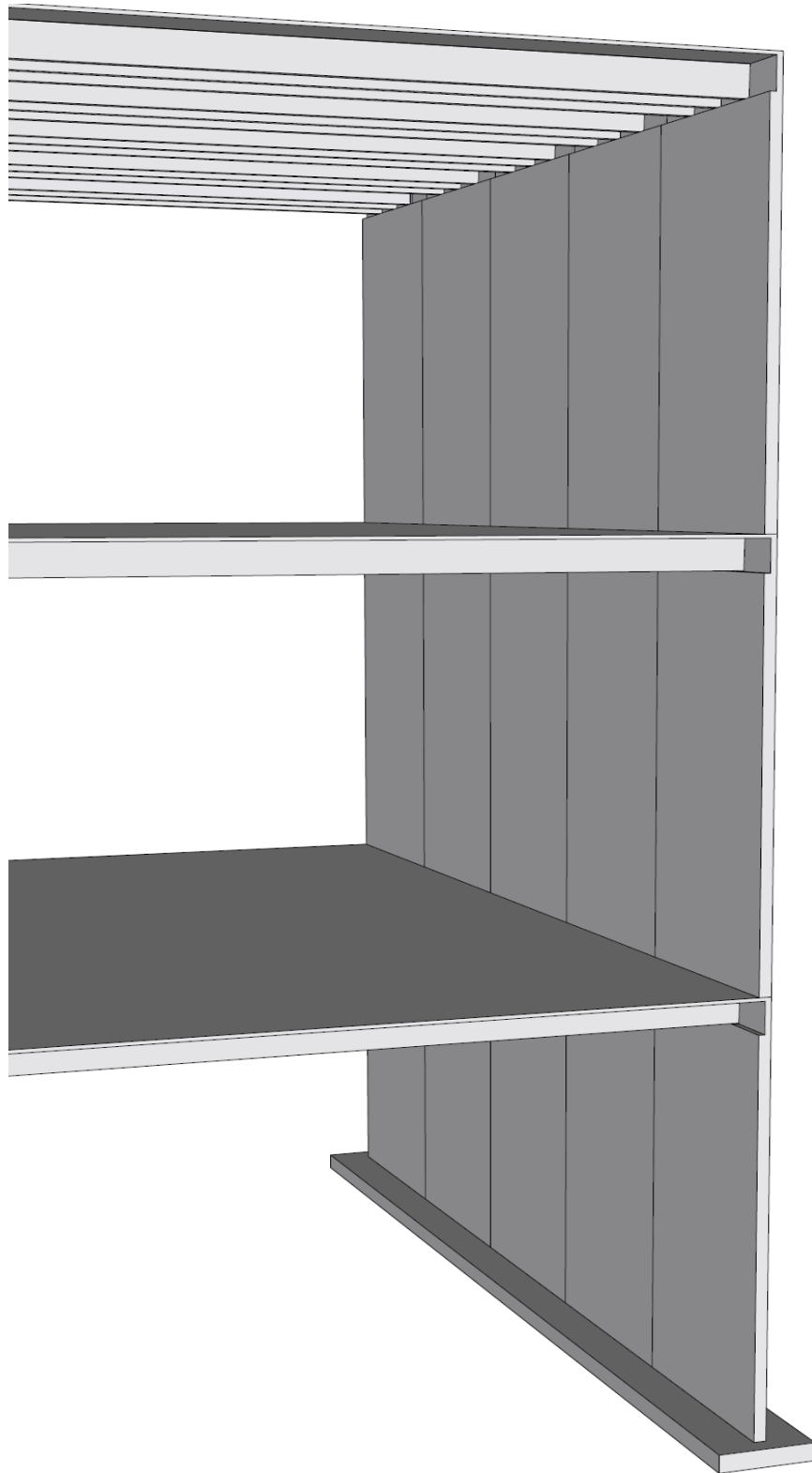


**Multi-Story Solid Tilt-Up Wall Panel Analysis and Design (ACI 551)**



**Reinforced Concrete Multi-Story Tilt-Up Wall Panel Analysis (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 as shown in Example B.5 of ACI 551.2R-15. The assumed tilt-up wall panel section and reinforcement are investigated using the procedure in ACI 551 and compared with the results of [spWall](#) engineering software program from [StructurePoint](#).

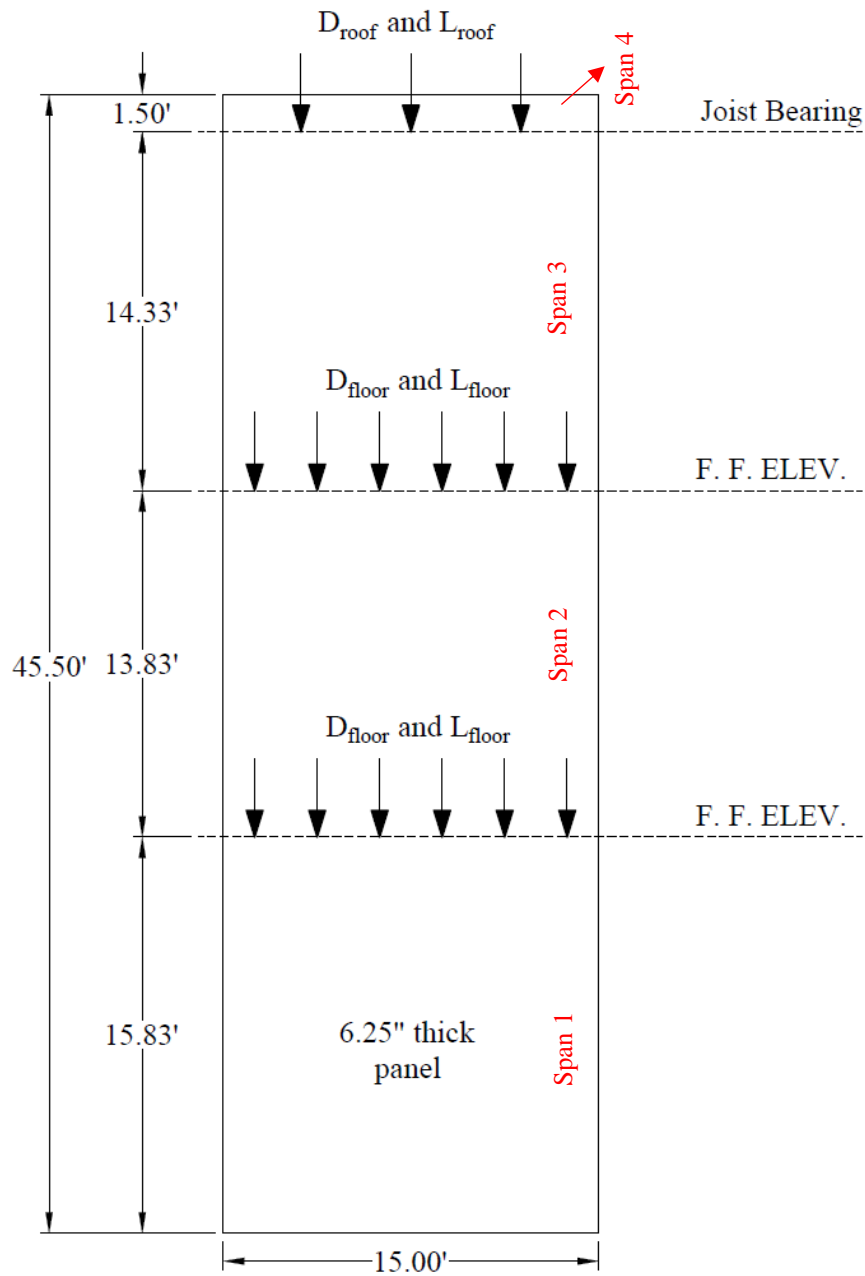


Figure 1 – Reinforced Concrete Multi-Story Tilt-Up Wall Panel Geometry

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**Code**

Building Code Requirements for Structural Concrete (ACI 318-11) and Commentary (ACI 318R-11)

**Reference**

Design Guide for Tilt-Up Concrete Panels, ACI 551.2R-15, 2015, Example B.5

[spWall](#) Engineering Software Program Manual v5.01, STRUCTUREPOINT, 2016

**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 design 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

### 4.1. Loads and Load Combinations

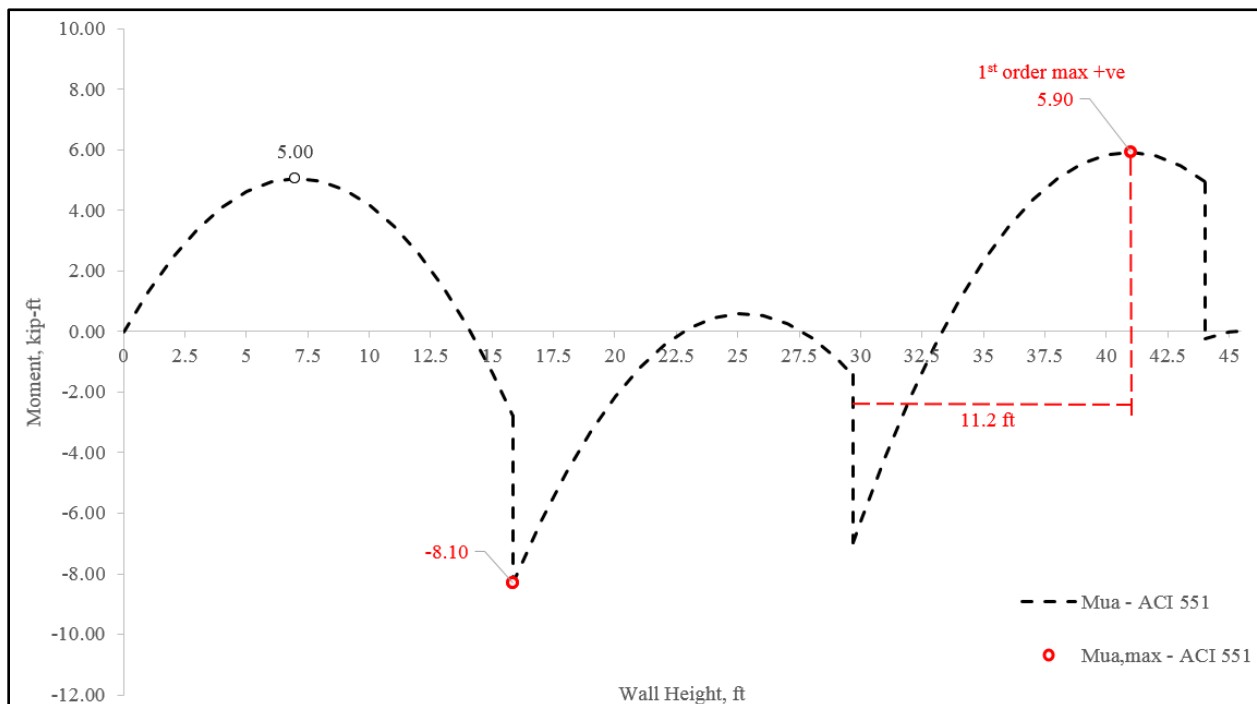
Roof dead load	= 3 x 2.4 = 7.2 kip
Roof live load	= 3 x 2.5 = 7.5 kip
Floor dead load	= 6 x 2.4 = 17.7 kip
Floor live load	= 6 x 2.5 = 30 kip
Wind load	= 27.2 psf (out of plane)
	= 0.00 psf (in plane)

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

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.

### 4.2. Wall First Order Structural Analysis

Using the loads calculated in the previous section for load combination1, the reference provides a diagram of first order moment comparable to the diagram shown below obtained as shown later in this example.



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

#### 4.3. 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:

$$P_{um} = 1.2 \times (7.2 + 5.51) + 1.6 \times 7.5 = 27.3 \text{ kip}$$

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

$$A_{se} = A_s + \frac{P_{um} \times h}{2 \times f_y \times d} = 4.84 + \frac{27.3 \times 6.25}{2 \times 60 \times (6.25 / 2)} = 5.29 \text{ in.}^2 \quad \text{ACI 318-11 (R14.8.3)}$$

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

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

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

$$\frac{c}{d} = \frac{0.611}{3.13} = 0.195 < 0.375 \therefore \text{tension-controlled} \quad \text{ACI 318-11 (R9.3.2.2)}$$

$$\phi = 0.9 \quad \text{ACI 318-11 (9.3.2)}$$

$$I_{cr} = n \times A_{se} \times (d - c)^2 + \frac{l_w \times c^3}{3} \quad \text{ACI 318-11 (Eq. 14-7)}$$

$$E_c = 57,000 \times \sqrt{f'_c} = 57,000 \times \sqrt{4,000} = 3,605,000 \text{ psi} \quad \text{ACI 318-11 (8.5.1)}$$

$$n = \frac{E_s}{E_c} = \frac{29,000}{3,605} = 8.0 > 6.0 \text{ (o.k.)} \quad \text{ACI 318-11 (14.8.3)}$$

$$I_{cr} = 8.0 \times 5.29 \times (3.13 - 0.611)^2 + \frac{(15 \times 12) \times 0.611^3}{3} = 283 \text{ in.}^4 \quad \text{ACI 318-11 (Eq. 14-7)}$$

$$M_u = \frac{M_{ua}}{1 - \frac{P_{um}}{0.75 \times K_b}} \quad \text{ACI 318-11 (Eq. 14-6)}$$

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 318-11 (14.8.3)

$$K_b = \frac{48 \times E_c \times I_{cr}}{5 \times l_c^2} = \frac{48 \times 3605 \times 283}{5 \times (14.3 \times 12)^2} = 332 \text{ kip}$$

$$M_u = \frac{5.9}{1 - \frac{27.3}{0.75 \times 332}} = 6.62 \text{ ft-kip}$$

## 5. Tilt-Up Wall Flexural Strength

According to ACI 318-11 (14.8.2.4), the reinforcement shall provide design capacity greater than cracking capacity.

### 6.1. Wall Cracking Moment Capacity ( $M_{cr}$ )

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

$$f_r = 7.5\lambda\sqrt{f'_c} = 7.5 \times 1.0 \times \sqrt{4,000} = 474.3 \text{ psi} \quad \text{ACI 318-11 (Eq. 9-10)}$$

$$I_g = \frac{l_w h^3}{12} = \frac{(15 \times 12) \times 6.25^3}{12} = 3662 \text{ in.}^4$$

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

$$M_{cr} = \frac{f_r I_g}{y_t} = \frac{474.3 \times 3662}{3.13} \times \frac{1}{1000} \times \frac{1}{12} = 46.3 \text{ ft-kip} \quad \text{ACI 318-11 (Eq. 9-9)}$$

### 6.2. Wall Flexural Moment Capacity ( $\phi M_n$ )

For load combination #1:

$$M_n = A_{se} \times f_y \times \left( d - \frac{a}{2} \right) = 5.29 \times 60 \times \left( 3.13 - \frac{0.519}{2} \right) = 75.89 \text{ ft-kip}$$

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

$$\phi M_n = \phi \times M_n = 0.9 \times 75.89 = 68.3 \text{ ft-kip} > M_u = 6.62 \text{ ft-kip} \quad \text{(o.k.)} \quad \text{ACI 318-11 (14.8.3)}$$

$$\phi M_n = 68.3 \text{ ft-kip} > M_{cr} = 46.3 \text{ ft-kip} \quad \text{(o.k.)} \quad \text{ACI 318-11 (14.8.2.4)}$$

$$\Delta_u = \frac{M_u}{0.75 \times K_b} = \frac{6.62 \times 12}{0.75 \times 332} = 0.319 \text{ in.} \quad \text{ACI 318-11 (Eq. 14-5)}$$

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)	+5.00	+8.50	1.700*	0.35
y = 40.86 ft (Span 3)	+5.90	+6.62	1.122	0.32
y = 15.83 ft (Span 2)	-8.10	-9.07*	1.120	0.00

\* the magnifier for span 1 exceeds the limit established in ACI 318-14 6.2.6 and should be investigated further when ACI 551 is updated from 318-11 to 318-14



### 6.3. Tilt-Up Wall Flexural Reinforcement

At the maximum positive moment location in span 3,  $I_{cr}$  equals 283 in.<sup>4</sup> corresponding to 11 #6 bars. At this location, the wall capacity far exceeds the maximum moment ( $\phi M_n = 68.3$  ft-kip  $\gg M_u = 6.62$  ft-kip), the corresponding cracking coefficient ( $0.75I_{cr}/I_g$ ) = 0.0580. 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 \(ACI 551\)](#)” example in [StructurePoint’s Design Examples Library](#).

### 7. **Tilt-Up Wall Axial Strength Check**

$$\frac{P_{um}}{A_g} = \frac{27.3 \times 1000}{6.25 \times (15 \times 12)} = 24.27 \text{ psi} < 0.06 \times f'_c = 0.06 \times 4,000 = 240 \text{ psi (o.k.)} \quad \underline{\underline{ACI 318-11 (14.8.2.6)}}$$

### 8. **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 7a, 7b, and 7c for detailed shear force, in-plane shear strength, and out of plane shear strength diagrams.

## 9. 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 318-11 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:  $1.2D + 0.5L_r + 1.0L + 1.0W$

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

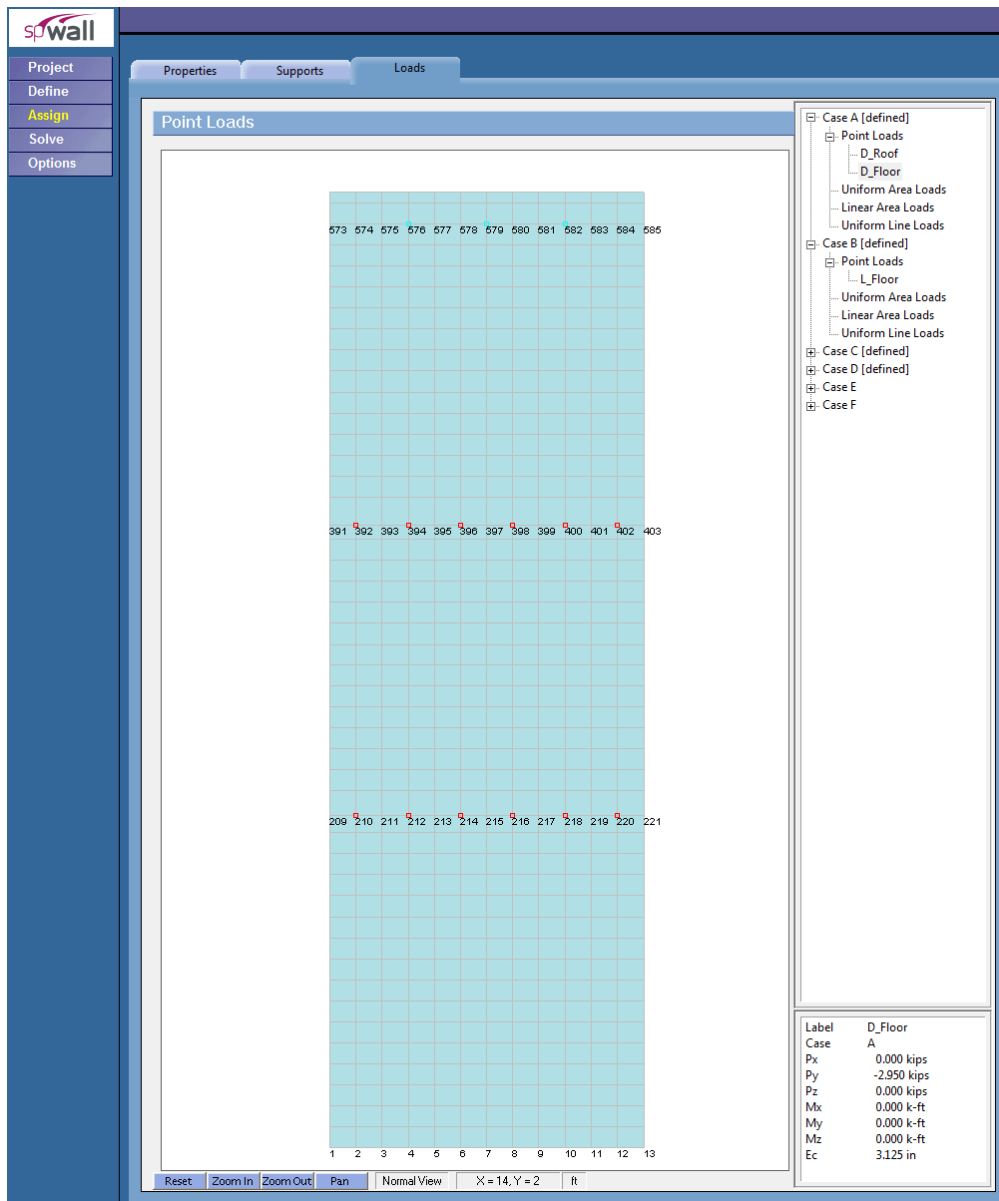
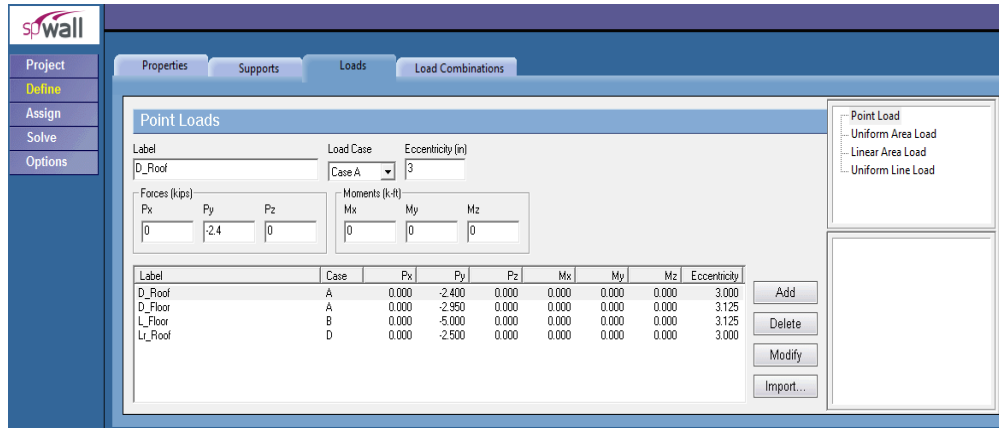


Figure 3 –Defining and Assigning Loads for Multi-Story Tilt-Up Wall Panel (spWall)

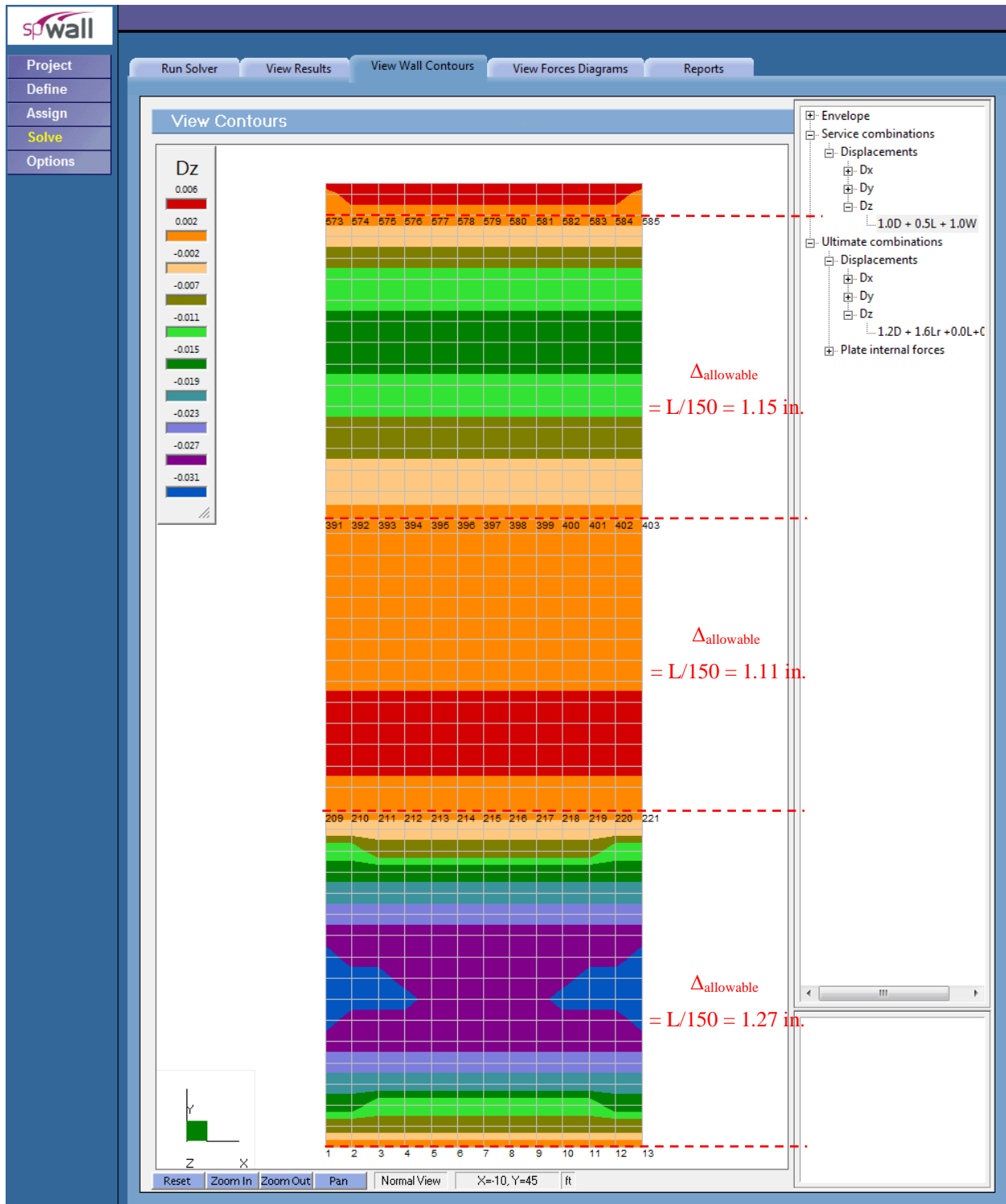


Figure 4 – Multi-Story Tilt-Up Wall Panel Service Displacements (spWall)

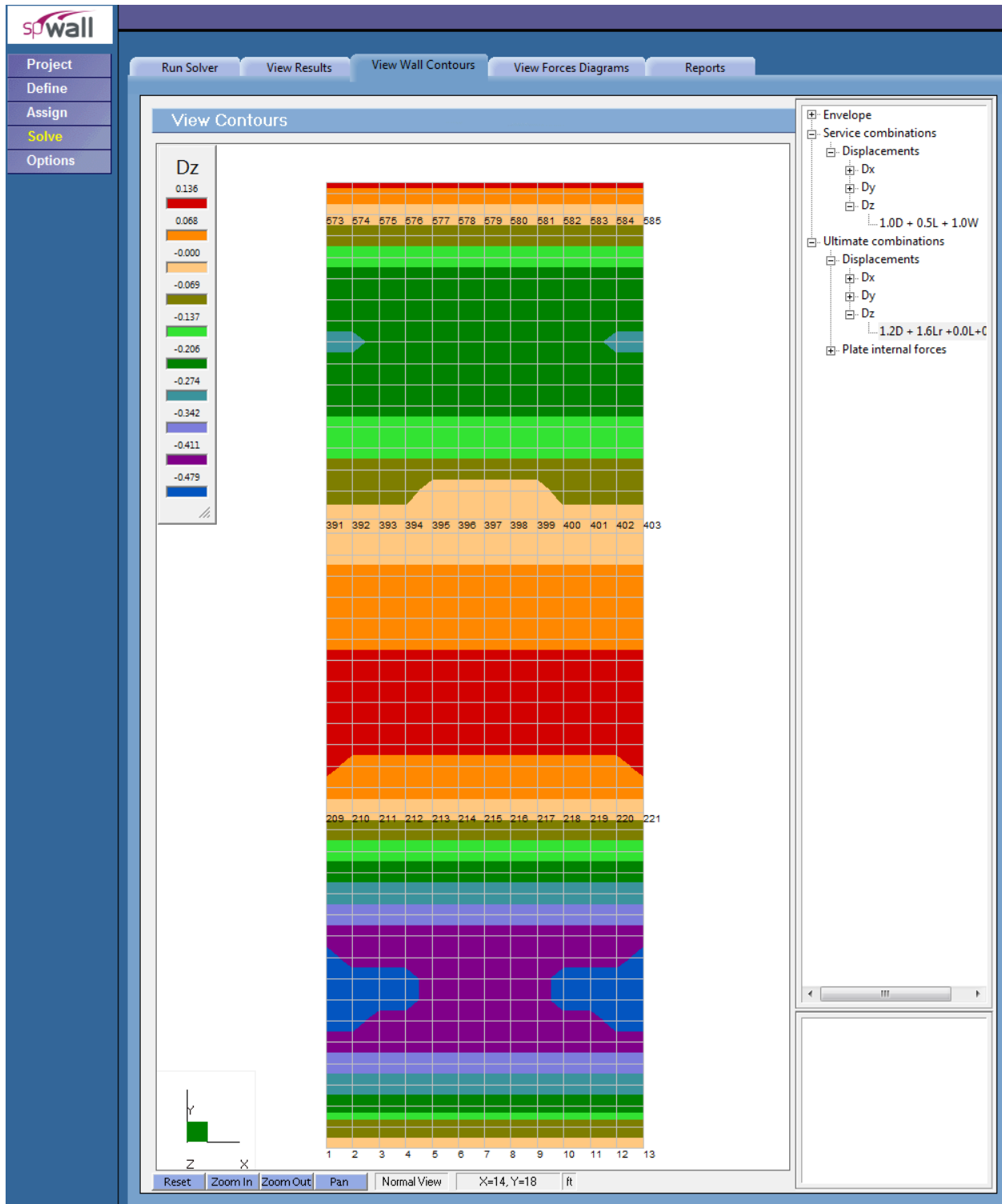


Figure 5 – Multi-Story Tilt-Up Wall Panel Ultimate Displacements (spWall)

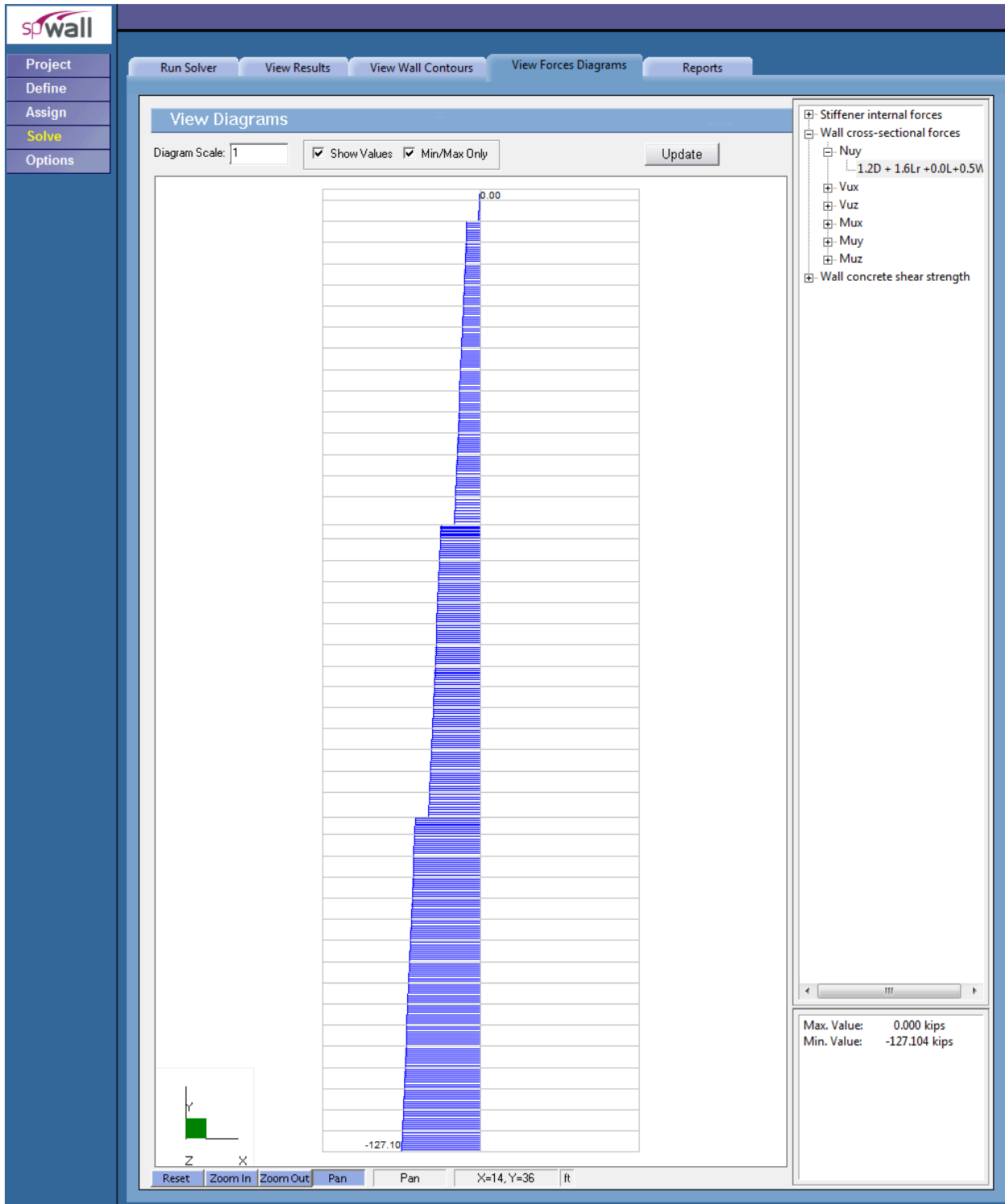


Figure 6 – Multi-Story Tilt-Up Wall Panel Axial Force Diagram (spWall)

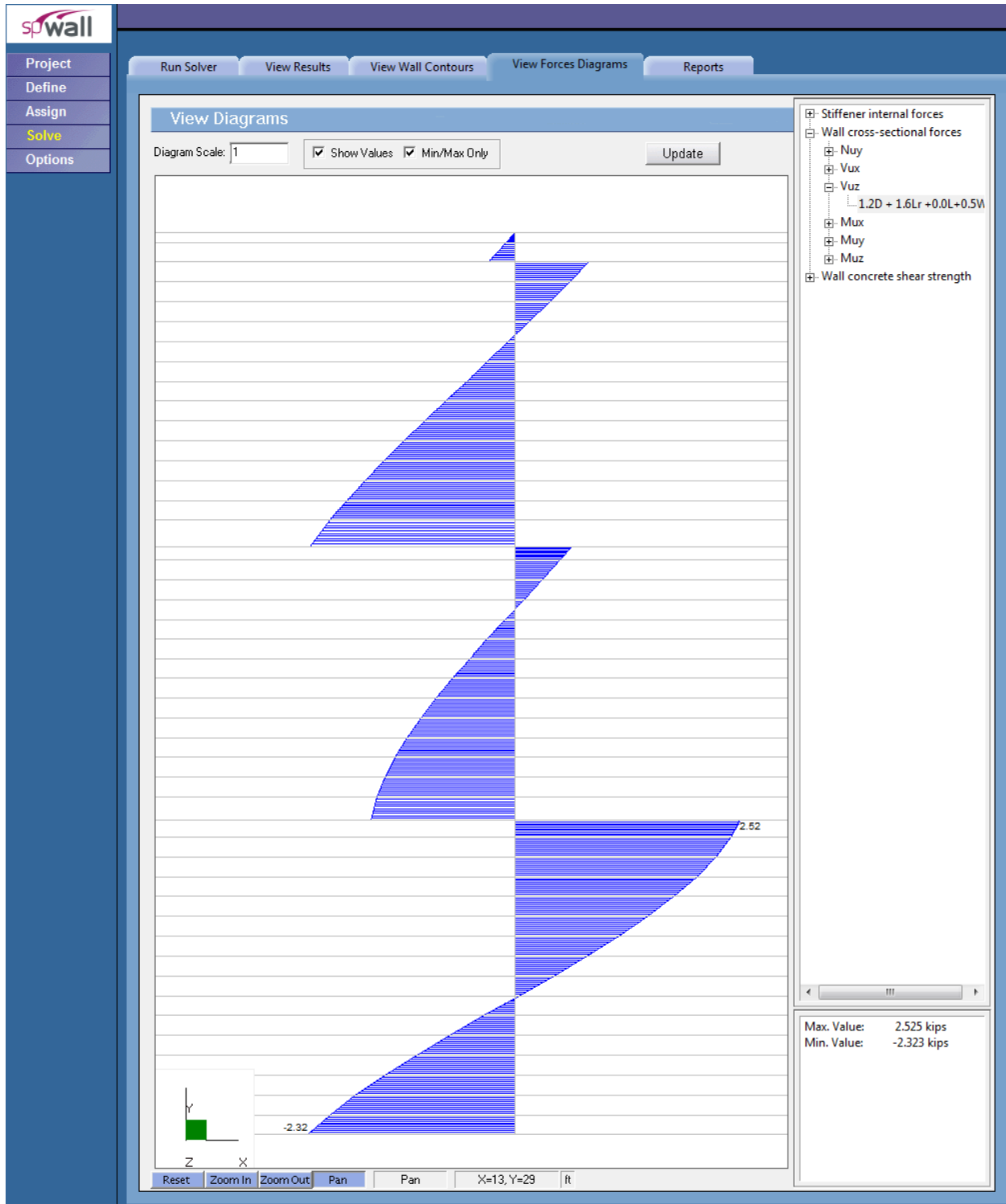


Figure 7a – Out-of-plane Shear Force Diagram (spWall)

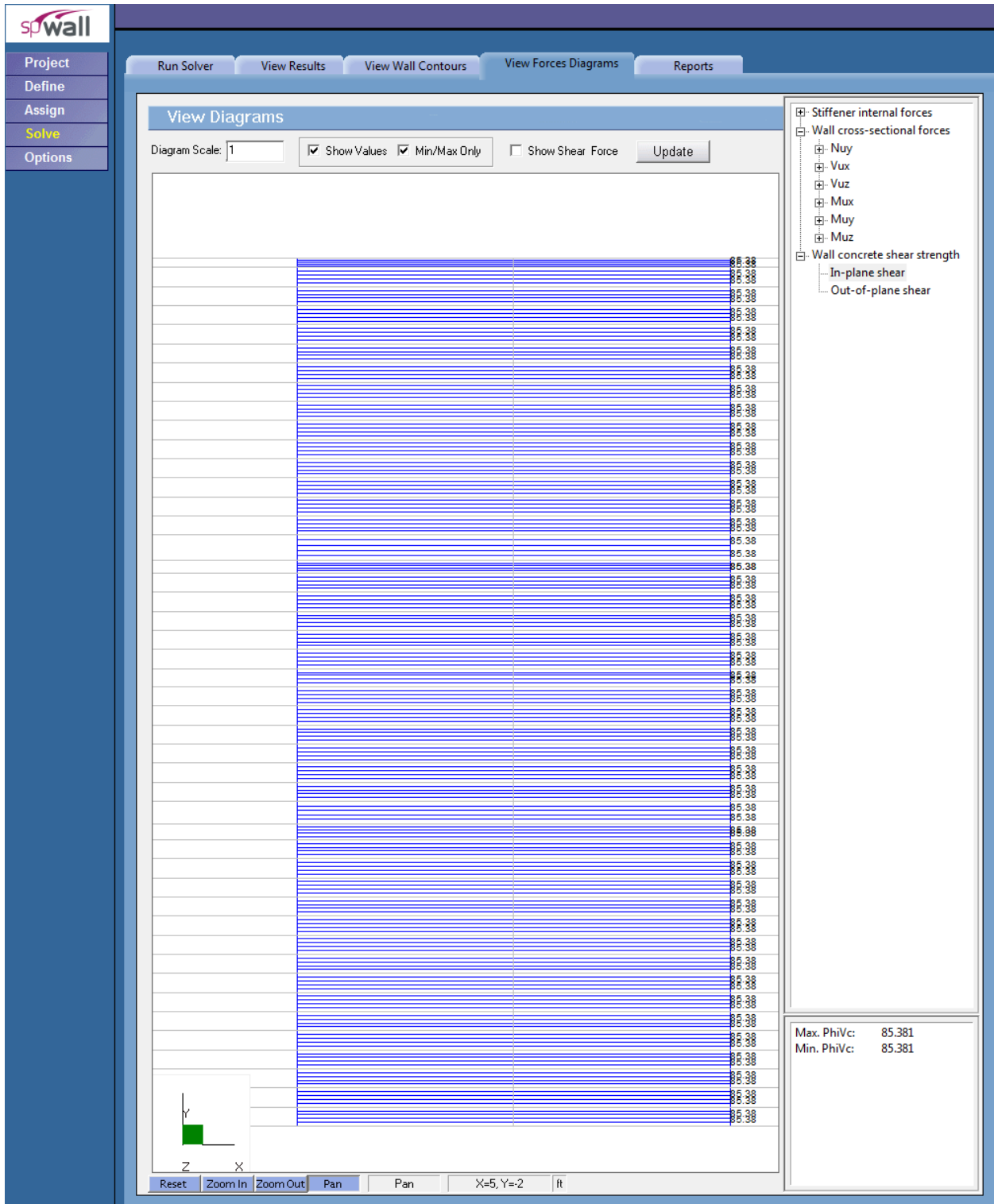


Figure 7b – In-plane Shear Strength Diagram (spWall)



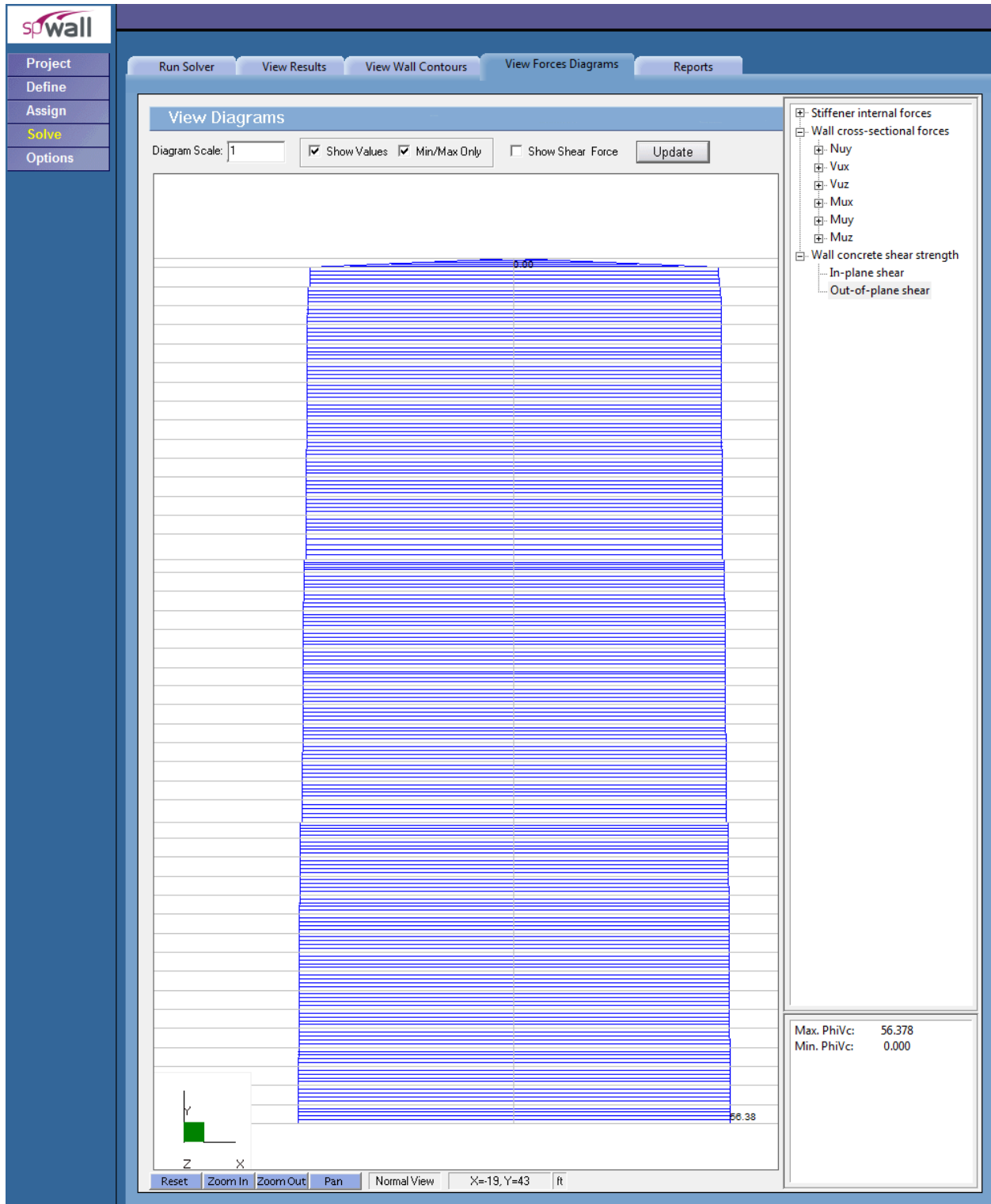


Figure 7c – Out-of-plane Shear Strength Diagram (spWall)

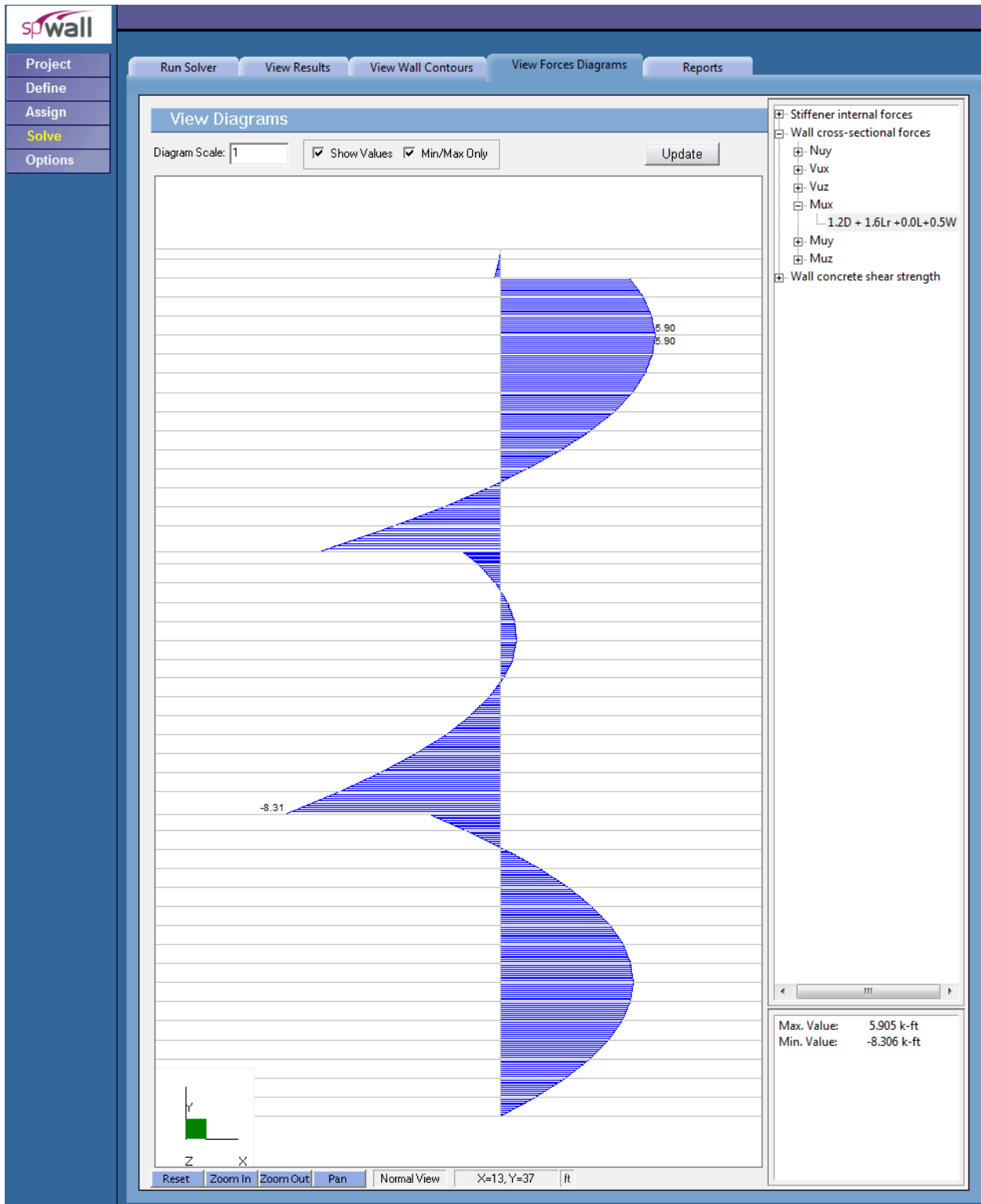


Figure 8 – Multi-Story Tilt-Up Wall First Order Moment ( $M_{110}$ ) Diagram (spWall)

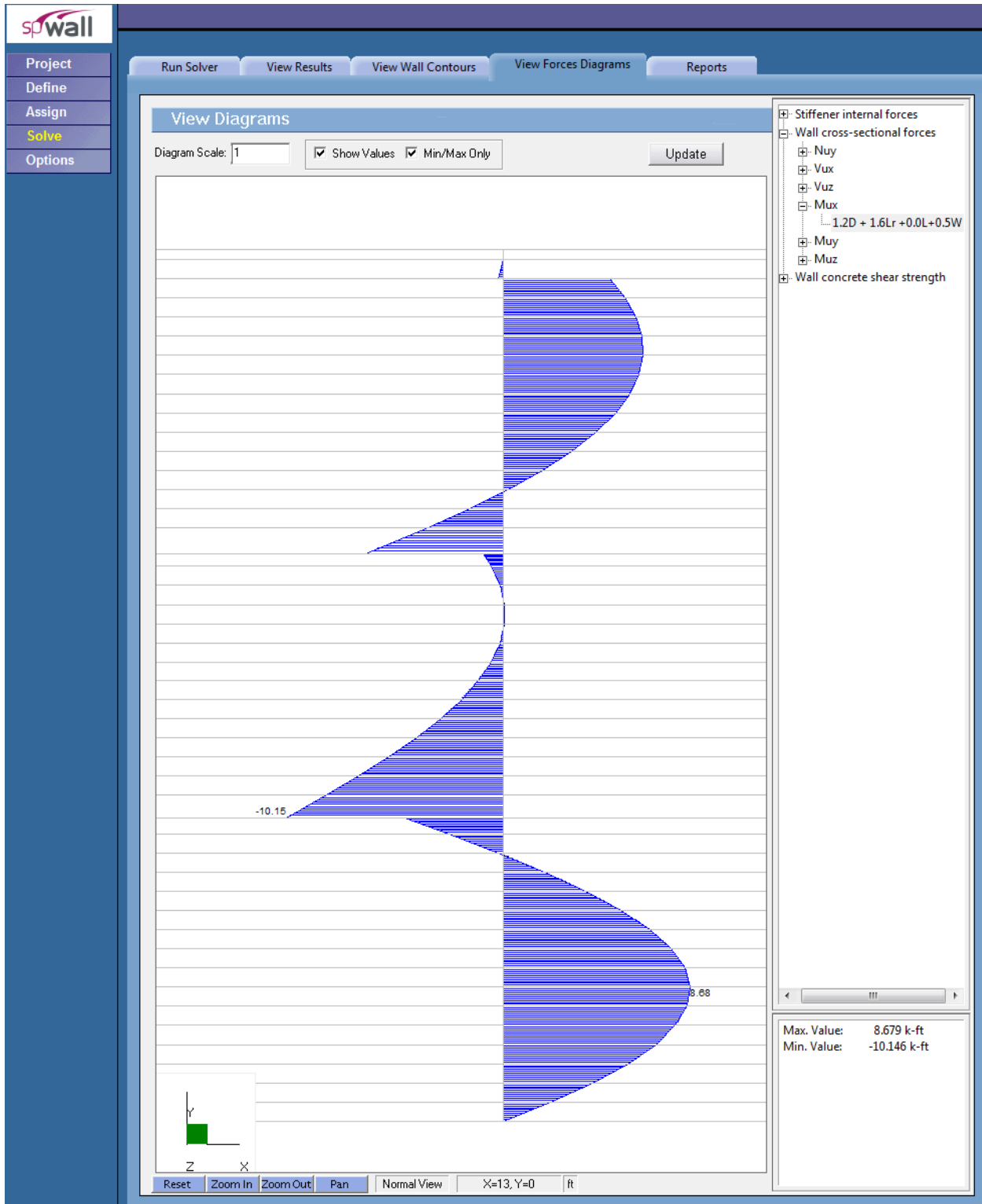


Figure 9 – Multi-Story Tilt-Up Wall second Order Moment ( $M_u$ ) Diagram (spWall)

Ultimate combinations | Wall cross-sectional forces | 1.2D + 1.6Lr + 0.0L+0.5W

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

No.	Wall Cross-section		In-plane Forces			Out-of-plane Forces		
	Y-coordinate	X-centroid	Vux	Nuy	Muz	Vuz	Mux	Muy
8-	7.000	0.000	2.6645e-015	-1.1726e+002	2.3386e-011	-1.1404e-002	5.0778e+000	4.4113e-014
8+	7.000	0.000	-1.6283e-013	-1.1726e+002	2.9306e-012	-1.1404e-002	5.0778e+000	4.1063e-012
17-	15.830	0.000	-1.3042e-013	-8.3603e+001	1.7815e-012	-1.9073e+000	-8.3056e+000	3.8055e-012
42-	41.000	0.000	6.1560e-014	-2.6968e+001	2.5796e-011	1.8725e-002	5.9047e+000	-1.4419e-012
42+	41.000	0.000	-1.0394e-013	-2.6968e+001	-2.8653e-013	1.8725e-002	5.9047e+000	2.6195e-012

Figure 10 – Multi-Story Tilt-Up Wall Panel Cross-Sectional Forces (First Order Analysis) (spWall)

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Ultimate combinations | Displacements | 1.2D + 1.6Lr + 0.0L+0.5W

Coordinate System: Global

Units:

Displacement (Dx, Dy, Dz): in

Node	Dx	Dy	Dz
105	-5.10e-004	-2.87e-003	-2.87e-001
106	-4.27e-004	-2.87e-003	-2.78e-001
107	-3.42e-004	-2.86e-003	-2.73e-001
108	-2.57e-004	-2.85e-003	-2.69e-001
109	-1.71e-004	-2.84e-003	-2.66e-001
110	-8.53e-005	-2.83e-003	-2.65e-001
111	-1.17e-016	-2.83e-003	-2.65e-001
112	8.53e-005	-2.83e-003	-2.65e-001
113	1.71e-004	-2.84e-003	-2.66e-001
114	2.57e-004	-2.85e-003	-2.69e-001
115	3.42e-004	-2.86e-003	-2.73e-001
116	4.27e-004	-2.87e-003	-2.78e-001
117	5.10e-004	-2.87e-003	-2.87e-001
209	-4.24e-004	-5.32e-003	-1.10e-017
210	-3.54e-004	-5.43e-003	-1.06e-015
211	-2.84e-004	-5.37e-003	-6.68e-016
212	-2.14e-004	-5.45e-003	-6.47e-016
213	-1.43e-004	-5.38e-003	-6.67e-016
214	-7.16e-005	-5.45e-003	-6.36e-016
215	-4.71e-016	-5.38e-003	-6.64e-016
216	7.16e-005	-5.45e-003	-6.36e-016
217	1.43e-004	-5.38e-003	-6.67e-016
218	2.14e-004	-5.45e-003	-6.47e-016
219	2.84e-004	-5.37e-003	-6.68e-016
220	3.54e-004	-5.43e-003	-1.06e-015
221	4.24e-004	-5.32e-003	-1.10e-017
495	-1.72e-004	-9.29e-003	-2.03e-001
496	-1.52e-004	-9.30e-003	-1.99e-001
497	-1.28e-004	-9.33e-003	-1.97e-001
498	-9.98e-005	-9.35e-003	-1.97e-001
499	-6.83e-005	-9.38e-003	-1.98e-001
500	-3.46e-005	-9.39e-003	-1.98e-001
501	-2.47e-015	-9.40e-003	-1.98e-001
502	3.46e-005	-9.39e-003	-1.98e-001
503	6.83e-005	-9.38e-003	-1.98e-001
504	9.98e-005	-9.35e-003	-1.97e-001
505	1.28e-004	-9.33e-003	-1.97e-001
506	1.52e-004	-9.30e-003	-1.99e-001
507	1.72e-004	-9.29e-003	-2.03e-001

$D_{z,averaged}$  @ 7 ft = 0.020 in.

$D_{z,averaged}$  @ 15.83 ft = 0.00 in.

$D_{z,averaged}$  @ 41 ft = 0.015 in.

Figure 11 – Ultimate Displacement at Critical Sections (First Order Analysis) (spWall)

Ultimate combinations | Wall cross-sectional forces | 1.2D + 1.6Lr + 0.0L + 0.5W

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

No.	Wall Cross-section		In-plane Forces			Out-of-plane Forces		
	Y-coordinate	X-centroid	Vux	Nuy	Muz	Vuz	Mux	Muy
8-	7.000	0.000	2.6645e-015	-1.1726e+002	2.3386e-011	5.1094e-002	8.6791e+000	6.4304e-013
8+	7.000	0.000	-1.6283e-013	-1.1726e+002	2.9518e-012	5.1094e-002	8.6787e+000	2.1032e-012
17-	15.830	0.000	-1.3042e-013	-8.3603e+001	1.8027e-012	-1.6190e+000	-1.0146e+001	2.6885e-012
41-	40.000	0.000	6.1560e-014	-2.8374e+001	2.5699e-011	-7.2244e-002	6.4846e+000	3.7970e-013
41+	40.000	0.000	-1.0394e-013	-2.8374e+001	-1.8031e-013	-7.2244e-002	6.4843e+000	1.8433e-012

Figure 12 – Multi-Story Tilt-Up Wall Panel Cross-Sectional Forces (second Order Analysis) (spWall)

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Ultimate combinations | Displacements | 1.2D + 1.6Lr + 0.0L + 0.5W

Coordinate System: Global

Units:

Displacement (Dx, Dy, Dz): in

Node	Dx	Dy	Dz
92	-5.06e-004	-2.54e-003	-4.79e-001
93	-4.22e-004	-2.53e-003	-4.65e-001
94	-3.37e-004	-2.51e-003	-4.55e-001
95	-2.51e-004	-2.50e-003	-4.48e-001
96	-1.66e-004	-2.49e-003	-4.44e-001
97	-8.28e-005	-2.48e-003	-4.42e-001
98	-8.84e-017	-2.48e-003	-4.41e-001
99	8.28e-005	-2.48e-003	-4.42e-001
100	1.66e-004	-2.49e-003	-4.44e-001
101	2.51e-004	-2.50e-003	-4.48e-001
102	3.37e-004	-2.51e-003	-4.55e-001
103	4.22e-004	-2.53e-003	-4.65e-001
104	5.06e-004	-2.54e-003	-4.79e-001
209	-4.24e-004	-5.32e-003	8.00e-017
210	-3.54e-004	-5.43e-003	-1.25e-015
211	-2.84e-004	-5.37e-003	-7.43e-016
212	-2.14e-004	-5.45e-003	-6.97e-016
213	-1.43e-004	-5.38e-003	-7.31e-016
214	-7.16e-005	-5.45e-003	-6.79e-016
215	-4.71e-016	-5.38e-003	-7.27e-016
216	7.16e-005	-5.45e-003	-6.79e-016
217	1.43e-004	-5.38e-003	-7.31e-016
218	2.14e-004	-5.45e-003	-6.97e-016
219	2.84e-004	-5.37e-003	-7.43e-016
220	3.54e-004	-5.43e-003	-1.25e-015
221	4.24e-004	-5.32e-003	8.00e-017
495	-1.72e-004	-9.29e-003	-2.45e-001
496	-1.52e-004	-9.30e-003	-2.40e-001
497	-1.28e-004	-9.33e-003	-2.37e-001
498	-9.98e-005	-9.35e-003	-2.37e-001
499	-6.83e-005	-9.38e-003	-2.37e-001
500	-3.46e-005	-9.39e-003	-2.38e-001
501	-2.47e-015	-9.40e-003	-2.38e-001
502	3.46e-005	-9.39e-003	-2.38e-001
503	6.83e-005	-9.38e-003	-2.37e-001
504	9.98e-005	-9.35e-003	-2.37e-001
505	1.28e-004	-9.33e-003	-2.37e-001
506	1.52e-004	-9.30e-003	-2.40e-001
507	1.72e-004	-9.29e-003	-2.45e-001

$D_{z,averaged}$  @ 7 ft = 0.45 in.

$D_{z,averaged}$  @ 15.83 ft = 0.00 in.

$D_{z,averaged}$  @ 40 ft = 0.24 in.

Figure 13 – Ultimate Displacement at Critical Sections (Second Order Analysis) (spWall)

## 10. Design Results Comparison and Conclusions

Moment	Location	Solution	$M_{ua}$ (kip-ft)	$M_u$ (kip-ft)	$D_{z,ultimate}$ (in.)
Max Positive	y = 7 ft (Span 1)	Reference	5.00	---**	---**
		Hand	5.00	8.50	0.35
		spWall	5.07	8.49	0.45
	y = 40 ft (Span 3)	Reference	5.90	6.62	0.32
		Hand	5.90	6.62	0.32
		spWall	5.91	6.46	0.24
Max Negative	y = 15.83 ft (Span 2)	Reference	-8.10	-9.07*	0.00
		Hand	-8.10	-9.07*	0.00
		spWall	-8.32	-10.07	0.00
* 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 and the reference 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 ACI 551 design guide illustrates tilt-up concrete walls analysis using the provisions of Chapter 14 of the ACI 318-11. Most walls, and especially slender walls, are widely evaluated using provisions from the “Alternative design of slender walls” in Section 14.8. The same provisions are presented in ACI 318-14 but reorganized in different chapters with slightly revised terminology. The provisions (or method) are applicable when the following specific conditions are met:

- The wall can be designed as simply supported ACI 318-11 (14.8.2.1)
- The maximum moments and deflections occurring at midspan ACI 318-11 (14.8.2.1)
- The wall must be axially loaded ACI 318-11 (14.8.2.1)
- The wall must be subjected to an out-of-plane uniform lateral load ACI 318-11 (14.8.2.1)
- The cross section shall be constant over the height of the wall ACI 318-11 (14.8.2.2)
- The wall shall be tension-controlled ACI 318-11 (14.8.2.3)
- The reinforcement shall provide design strength greater than cracking strength ACI 318-11 (14.8.2.4)
- The concentrated loads application limits shall be met ACI 318-11 (14.8.2.5)
- The vertical stress limit at midheight shall be met ACI 318-11 (14.8.2.6)

For multi-story panels and panels with openings, ACI 551 adapted the alternative design method even though several of the conditions above are not or cannot be met. The comparison between the reference and the FEA

results 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 the reference example, this issue is illustrated in Figures 14 and 15 for Load Combination 1 (1.2D + 1.6Lr + 0.5W) where:

ACI 551 (presented)  $M_{u,negative} = -9.07$  kip-ft (Using positive moment magnification factor from span 3).

(Recommended)  $M_{u,negative} = -13.38$  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 reference 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 15.

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 reference example, this issue is illustrated for Load Combination 1 (1.2D + 1.6Lr + 0.5W) where in the following table the maximum positive design moment moved from span 3 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	+5.90	+6.62	Span 3	-8.10	-9.07	Span 1
Recommended	+5.00	+10.03	<i>Span 1</i>	-8.10	-13.38	Span 1

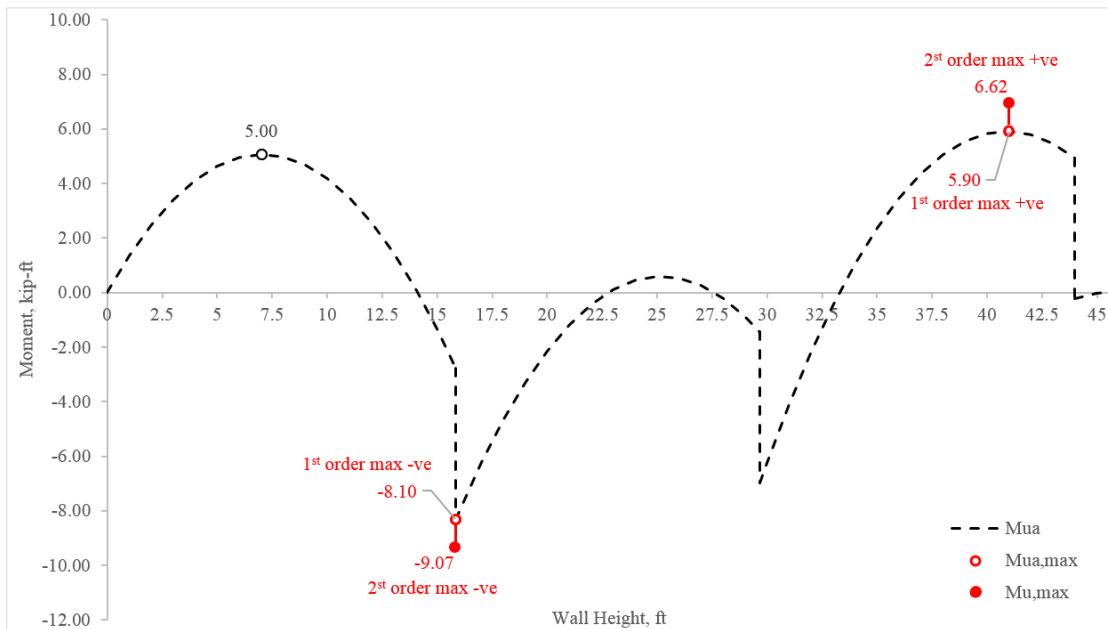


Figure 14 – First Order Moment Diagram and Second Order Maximum Moments (ACI 551 Procedure)

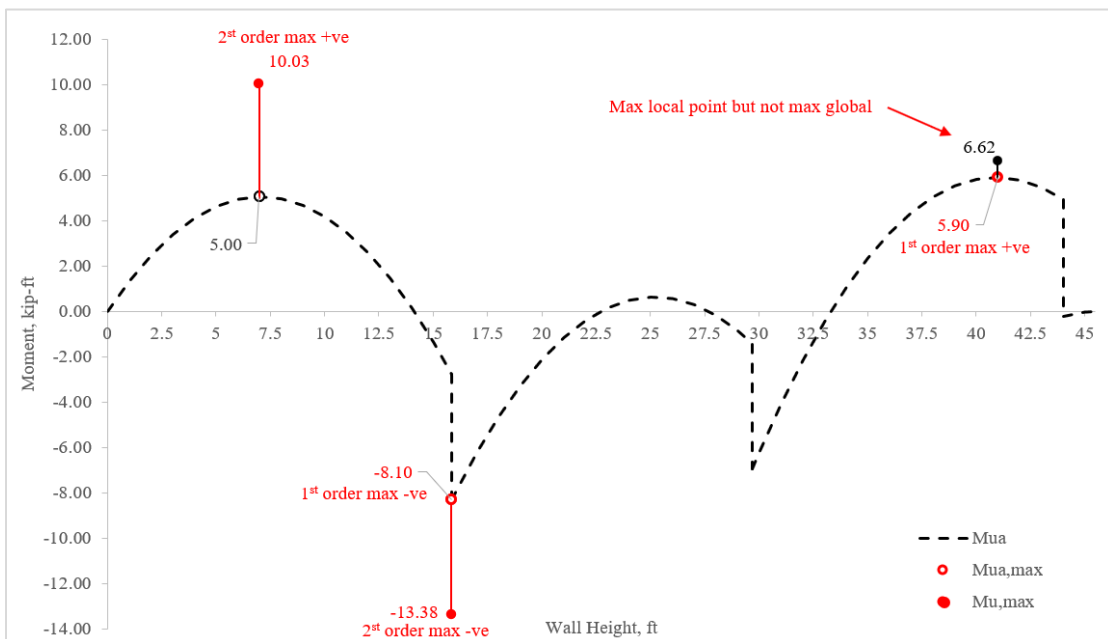
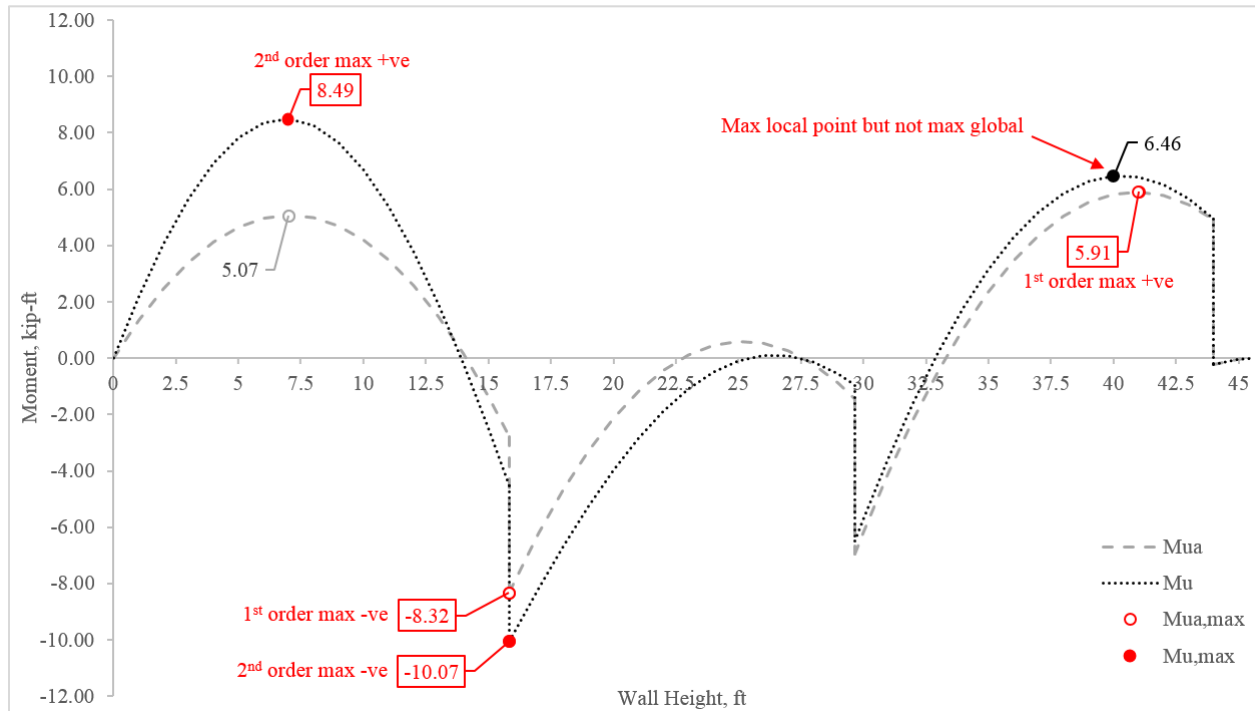


Figure 15 – Recommended Magnified Design Moments



Conclusions and Observations

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



**Figure 16 – First and Second Order Moment Diagrams (Using [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 ACI 551 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
ACI 551 Recommended	+5.00	+10.03	1.98	Span 1	-8.10	-13.38	1.65	Span 1
FEA - spWall	+5.07	+8.49	1.67	Span 1	-8.32	-10.07	1.21	Span 1

Table 5 - Comparison of Recommended ACI 551 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)
ACI 551 - Recommended	117.0	105.0	27.3
FEA - spWall	117.3	104.8	27.0

Table 6 - Comparison of Recommended ACI 551 with FEA (Out-of-Plane Shear Forces)

Method	$V_u$ , kip			$\phi V_c$ , kip		
	y = 7 ft	y = 15.83 ft	y = 40.86 ft	y = 7 ft	y = 15.83 ft	y = 40.86 ft
ACI 551 - Recommended	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.
FEA - spWall	0.05	2.52	0.16	56.15	55.85	54.00