



ADAPT-Wall Designer (AWD) Operation and Theory Manual

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1 Adapt-Wall Designer Overview

ADAPT-Wall Designer (AWD) is an integrated design module for **ADAPT-Builder** and provides tools for the design of reinforced concrete bearing and shear walls. The program includes options for the design of zone-less (no boundary elements) walls including panel reinforcement only, or walls with both boundary elements and panel reinforcement. This version of the program is compatible with prismatic walls where the boundary elements are of the same thickness as the wall panel. ADAPT-Wall Designer is currently compatible with ACI318-11 design code. The program can operate as a standalone executable but is commonly accessed and used through the integrated ADAPT-Builder GUI. For more information regarding usage and functionality for wall design directly through ADAPT-Builder, refer to the **ADAPT-Builder 20 Column & Wall Design Manual**. This document focuses primarily on the back-end functionality and theory related to the ADAPT-Wall Designer executable.

ADAPT-Builder also includes interoperability with the S-Concrete wall design application providing the user with additional design code selections, non-prismatic wall shapes (thickened boundary elements) and seismic design requirements.

Wall design actions are generated natively using ADAPT-Edge or ADAPT-Floor Pro. The program also includes the option to import wall reactions by use of the ADAPT-Integration Console from ETABs for the design of walls using the ADAPT-Wall Designer. When multiple, global solutions are captured within ADAPT-Builder using usage case modifiers, the user can select the solution reactions when designing walls. See **Figure 1-1**.

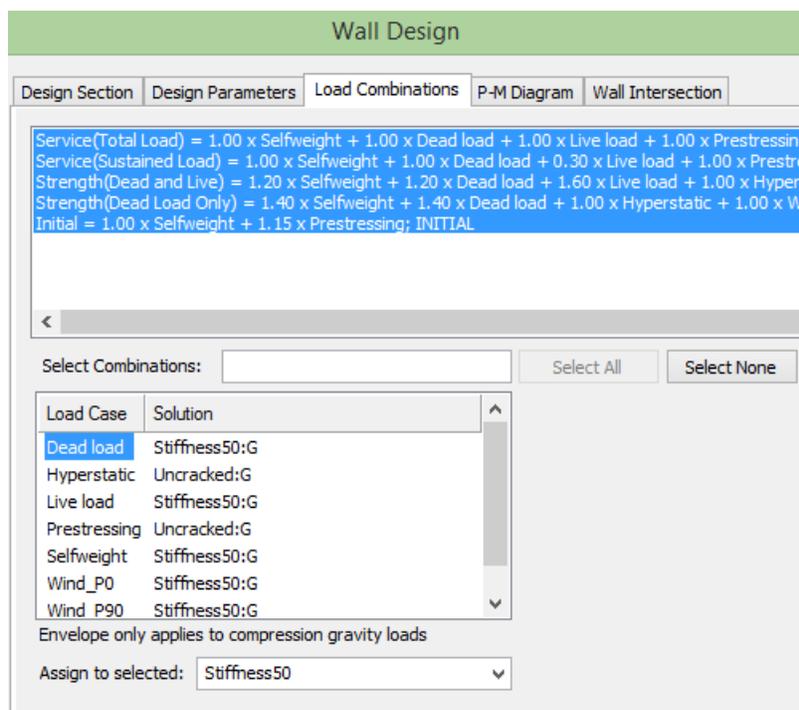


Figure 1-1 Wall Design Load Combinations

ADAPT-Wall Designer operates silently and is fully integrated within the ADAPT-Builder user interface. However, the application can be independently launched and used from accessing the program executable file in C:\Program Files (x86)\ADAPT\ADAPT-Builder 2019\wall design.exe. Walls that are modeled, analyzed, and processed using the wall designer are evaluated as design sections at the top and bottom of each wall belonging to an assigned pier. Individual wall design sections processed using ADAPT-Wall Designer are assigned an input data file, NAME_OF_SECTION.AWL. These files can be opened directly from FILE>Open within the ADAPT-Wall Designer interface. See **Figure 1-2**. The input files are stored in the **WallDesign** folder located in the main model directory for ADAPT-Builder models where the wall designer is used.

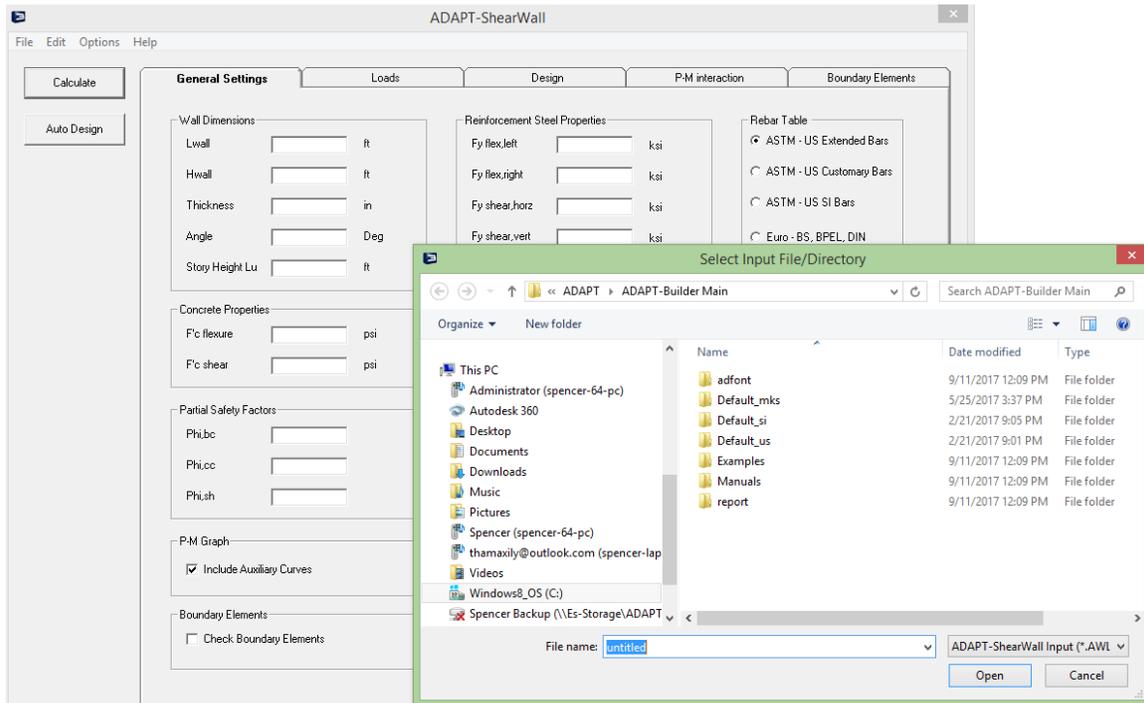


Figure 1-2 ADAPT-Wall Designer User Interface

2 Program Operability

The application operates in two modes:

- **The investigation mode ("Calculate" button in AWD and "Code Check" button in ADAPT-Builder)** can be used to verify if the assumed design settings are sufficient to satisfy the design requirements. In this mode, the program does not perform any adjustments of reinforcement quantities but checks the current set of reinforcement and wall properties against the selected design code requirements.
- **The Auto-Design mode ("Auto Design" button in AWD and "Design" button in ADAPT-Builder)** allows for automatic selection of the amount of main horizontal and vertical reinforcement for satisfy the requirements of flexure design (P-M Interaction) and shear design. The Auto-Design functionality has also been extended on the design of boundary zones, allowing for automatic selection of ties.

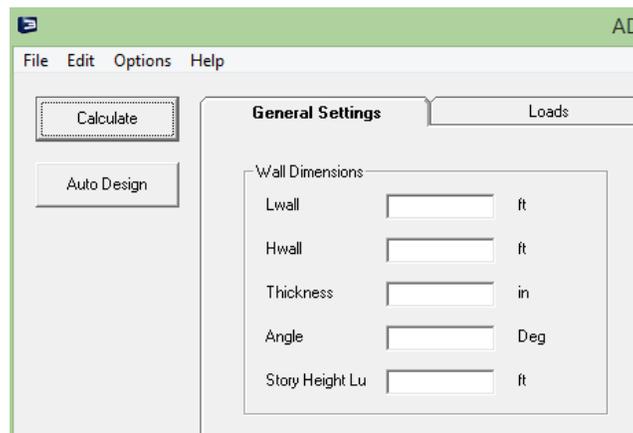


Figure 2-1 ADAPT Wall Designer Operability Options

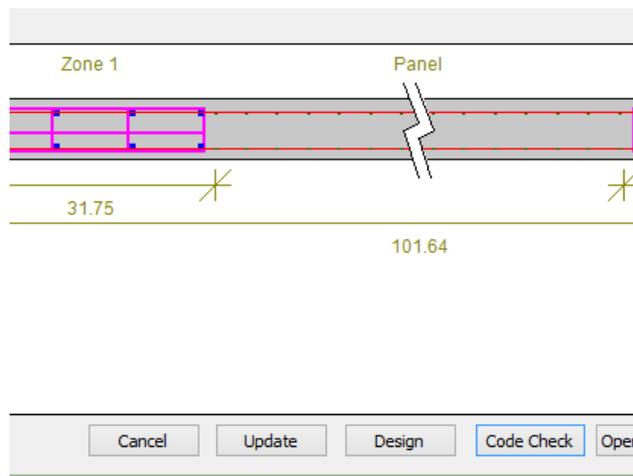


Figure 2-2 ADAPT-Builder Wall Design Operability Options

ADAPT

The application operates internally using the US "Imperial" unit system. The AWD user interface can operate in one of three possible unit systems" SI Metric, US Imperial, or MKS. It is possible to convert a project from one set of units to the other, simply by selecting another unit system using the menu item **Options→System of Units**. The existing project (or new project) will automatically get converted to the new unit system. Please note that multiple conversions may lead to some insignificant loss of accuracy of floating-point numbers.

Several reinforcement tables are implemented in the program, which are available from the **General Settings** pull-down menu item. The first selection "**ASTM - US Extended Bars**" was adopted as a default, custom bar group. The remaining rebar tables are using ADAPT's standard rebar definitions contained in the REBAR_DB.ADP file. When switching between different rebar tables, the program will attempt to automatically convert previous selection of bar sizes, to match the newly selected rebar table. However, the user should manually check if the program selected bar size matches the needs of the project.

The program GUI is provisioned to support different design codes. However, currently only ACI318-2011 is functional and implemented. For other design codes, the option for S-Concrete can be selected in ADAPT-Builder from **FEM→Wall Design→Design Parameters**.

The current state of design/investigation can be saved and reopened using a project file (.AWD). The file can contain both input and output values (if calculated).

3 ADAPT-Wall Designer Graphical User Interface (GUI)

The figures below described the different input and output dialogue windows and associated parameters for ADAPT-Wall Designer. When using ADAPT-Builder’s user interface for wall design with AWD selected as the design tool, the parameters shown in the windows below are replicated within Builder and mapped to wall designer for silent processing runs. The user is not required to input values unless directly in these interfaces unless operating AWD independent of ADAPT-Builder as a standalone application.

3.1 General Settings

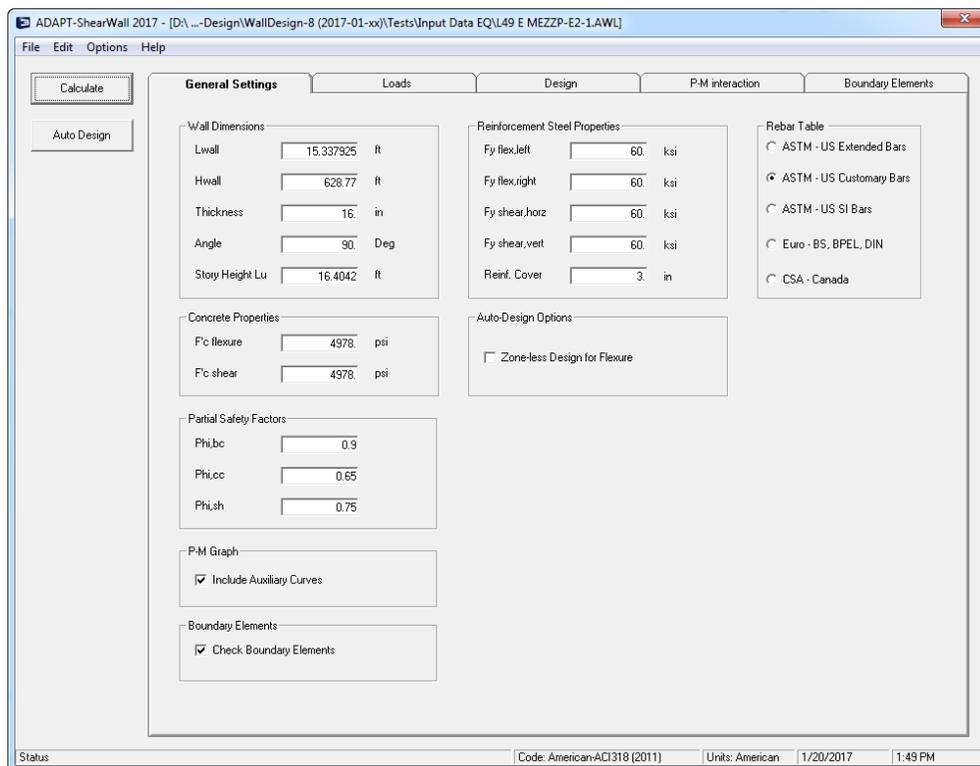


Figure 3-1 General Settings Input Window

- **Wall Dimensions** – Inputs are required for wall length (ft, m), total wall height (ft, m), thickness (in, mm), wall angle* (degrees), and story height (ft, m)
- **Concrete properties** – Concrete compressive strengths for flexure and shear (psi, MPa)
- **Reinforcement steel properties** – Reinforcement yield strength for zone and panel reinforcement (ksi, MPa) and rebar cover (in, mm)
- **Rebar Table** – Reinforcement library for definition of rebar and calculation of rebar (design mode). Options available are ASTM-US Extended, ASTM-US

Customary, ASTM – US SI, Euro – BS, BPEL, DIN and CSA-Canada. Reinforcement table data is found in the “rebar_db.adp” file located in the program files directory.

- **Partial safety factors** – Strength reduction factors, Phi, for bending, compression and shear.
- **Check boxes controlling additional functionalities** – Check of boundary element stress limitation or maximum concrete strain and option for zone-less design in flexure.

All fields in General Settings tab are strictly for input. *The value Angle is currently ignored and reserved for future development. It is assumed that the wall is analyzed in its local coordinate system, and the loads will be defined accordingly (Angle=0). Therefore, no angle transformations are performed.

3.2 Loads

The **Loads** tab contains the factored forces and moments for all considered load combinations. When utilizing AWD as the wall design option in ADAPT-Builder, the user has the option of selecting which load combinations are to be processed for design. Only combinations that include load cases with available solution reactions are available to be selected. When working in AWD as a standalone application, the user must enter the forces and moments in table format.

When using AWD as a standalone application, before entering the load values, the user should resize the load table using the field **Number of load cases**. The load labels and values can be entered manually into the grid control. The **minimum and maximum** fields contained in this tab are recalculated internally and do not need to be input or modified.

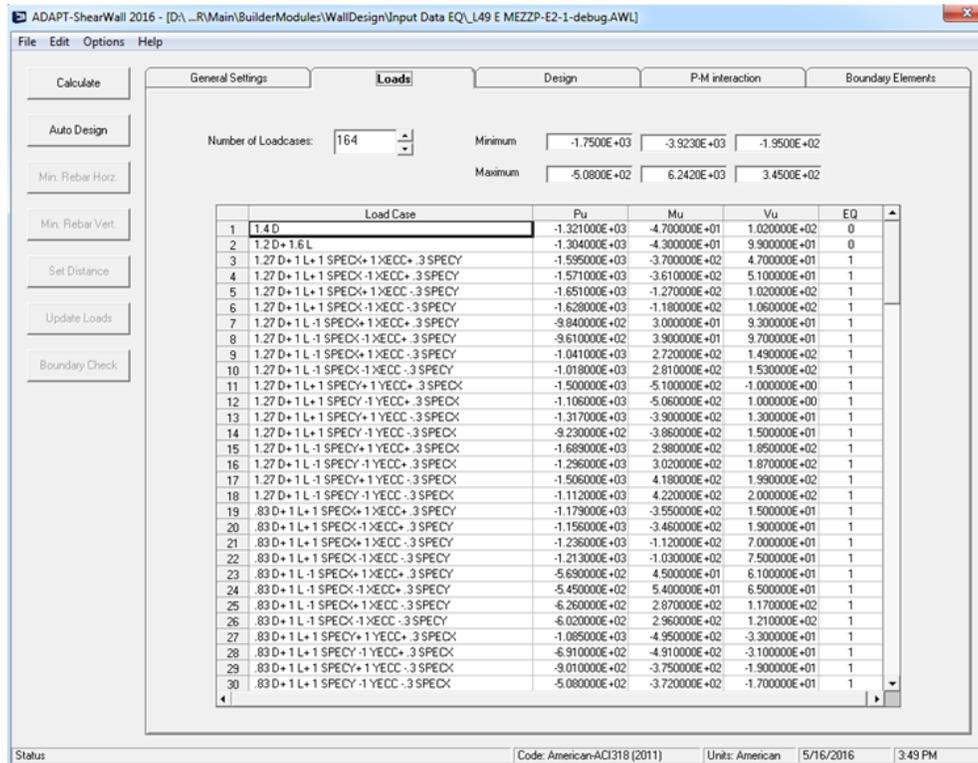


Figure 3-1 Loading Input Window

3.3 Design

The **Design** tab contains both input and output fields. Depending on the mode of operation (Investigation or Auto-design), some of the fields are for input only or can also contain the output values. The following fields are the input fields of this dialogue menu.

- **Rebar size at left** – Bar size for boundary zone left.
- **Rebar size at right** – Bar size for boundary zone right.
- **Number of bars at left** – Total bar quantity in boundary zone left.
- **Number of bars at right** – Total bar quantity in boundary zone right.
- **Bar spacing at left** – Bar spacing in boundary zone left in direction of wall length.
- **Bar spacing at right** – Bar spacing in boundary zone right in direction of wall length.
- **Curtains at left** – Number of bar rows at left boundary zone in direction perpendicular to direction of wall length.

- **Curtains at right** – Number of bar rows at right boundary zone in direction perpendicular to direction of wall length.
- **Number of face bars at left (for boundary element design)** – Number of bar columns at left boundary zone in direction of wall length.
- **Number of face bars at right (for boundary element design)** – Number of bar columns in right boundary zone in direction of wall length.
- **Horizontal bar size** – Horizontal bar size in panel.
- **Vertical bar size** – Vertical bar size in panel.
- **Number of horizontal bars** – Total bar quantity in panel of horizontal bars.
- **Number of vertical bars** – Total bar quantity in panel of vertical bars.
- **Horizontal bar spacing** – Bar spacing in panel of horizontal bars.
- **Vertical bar spacing** – Bar spacing in panel of vertical bars.

The fields in **bold** text are output fields in Auto-Design mode, but also serve as input fields (initial values for design). The fields listed above in regular text are input fields only. The remaining fields not listed above but shown in the image below are for output only.

The schematic of rebar distribution for vertical bars is presented below.

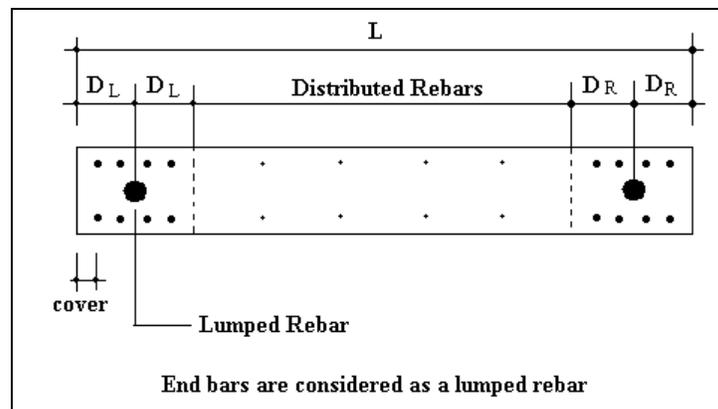


Figure 3-3 Rebar Distribution in wall

When performing investigation or design, the program will display the status messages, indicating success or failure conditions.

The auto-design algorithm operates such that the amount of left and right reinforcement to satisfy the flexure condition can be automatically adjusted, however there is no automatic adjustment of bar sizes (for left and right bars). The user selected bar sizes are used. The auto-design of shear reinforcement (horizontal and vertical) can result in program changing both the quantity and size of the bars.

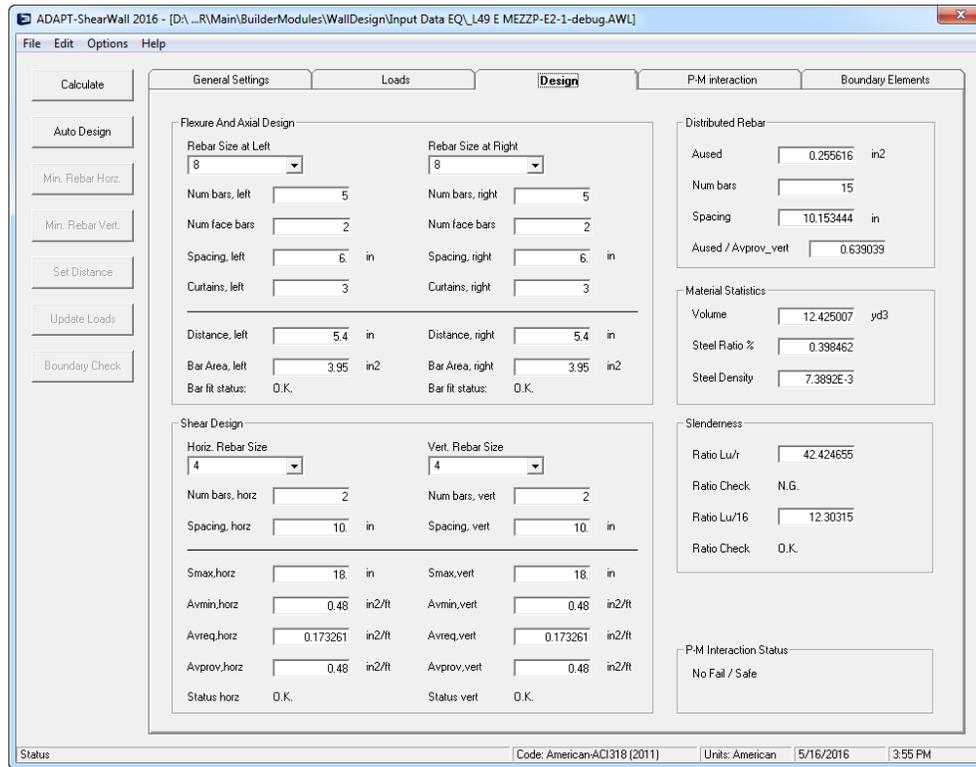


Figure 3-4 Design Input Window

3.4 P-M Interaction

The **P-M Interaction** tab contains the interaction diagram for axial force and moment. The interaction diagram in AWD is developed only the bending about the local r-r axis of the wall. When AWD is selected as the design tool in ADAPT-Builder, the interaction diagram is produced for the angle theta being 90 and 270 deg. This angle is measured between the local r-r and s-s axes as defined for walls in Builder. There are no input fields on this tab. The auxiliary curves can also be displayed if selected on the **General Settings** tab.

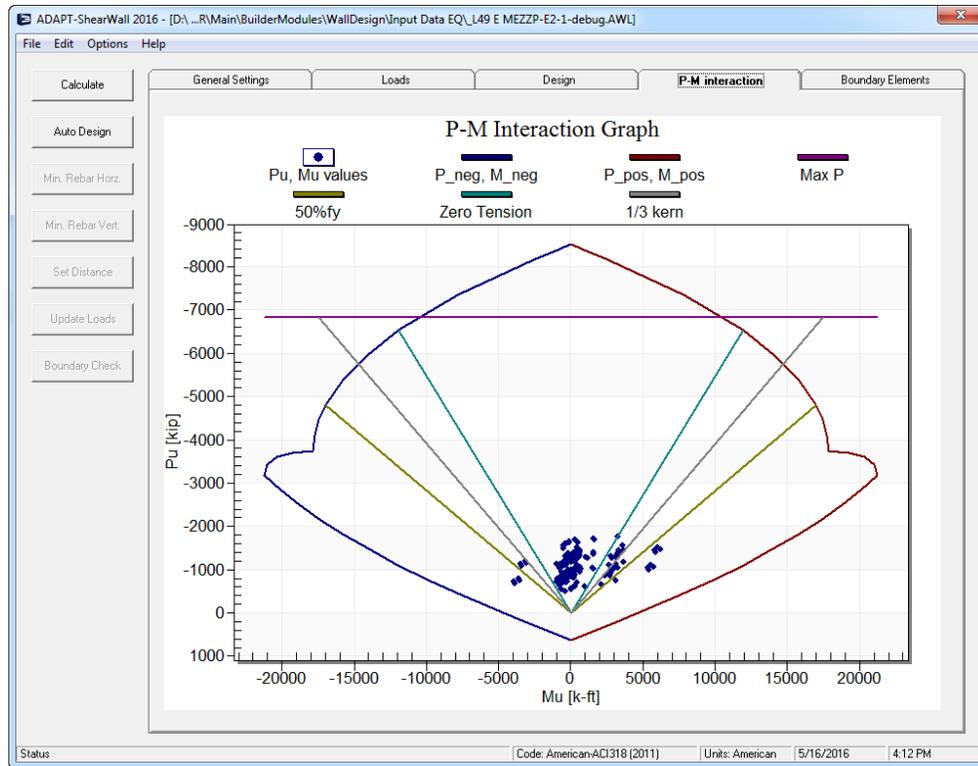


Figure 3-5 P-M Interaction Output Window - AWD

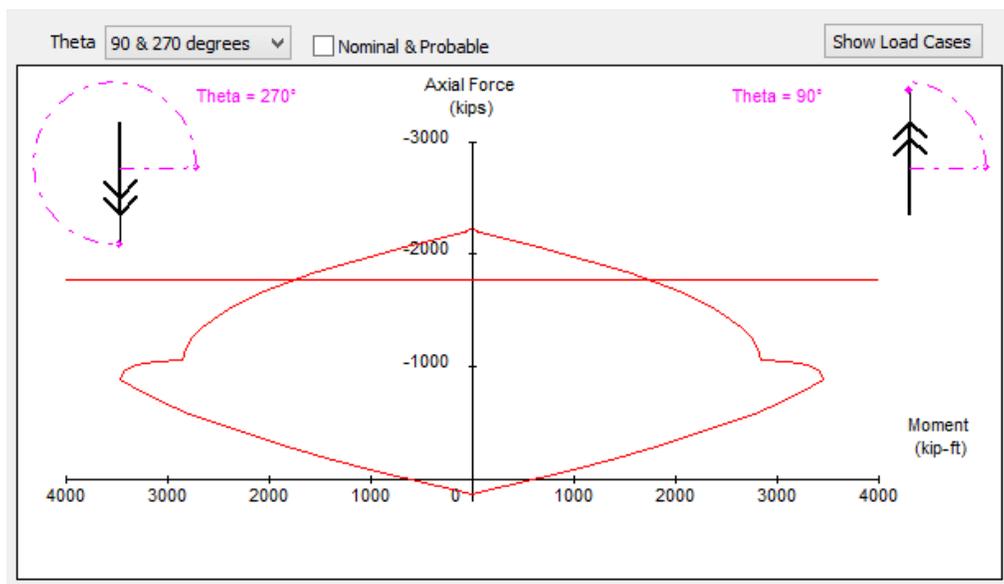


Figure 3-6 P-M Interaction Output Window – Builder

3.5 Boundary Elements

The **Boundary Elements** tab allows investigation and design of boundary zones. In the **General Settings** tab, the checkbox "Check boundary elements" has to be selected in order to enable boundary element calculations. The user must select design method ("Stress > 0.2 f_c " or "Strain > 0.003"). The load cases in the **Loads** tab need to have appropriate flags input in the column "EQ" Set the flag as 0 for non-seismic and 1 for seismic.

The input and output fields for boundary element ties are as follows in the graphical representation of left and right boundary zones.

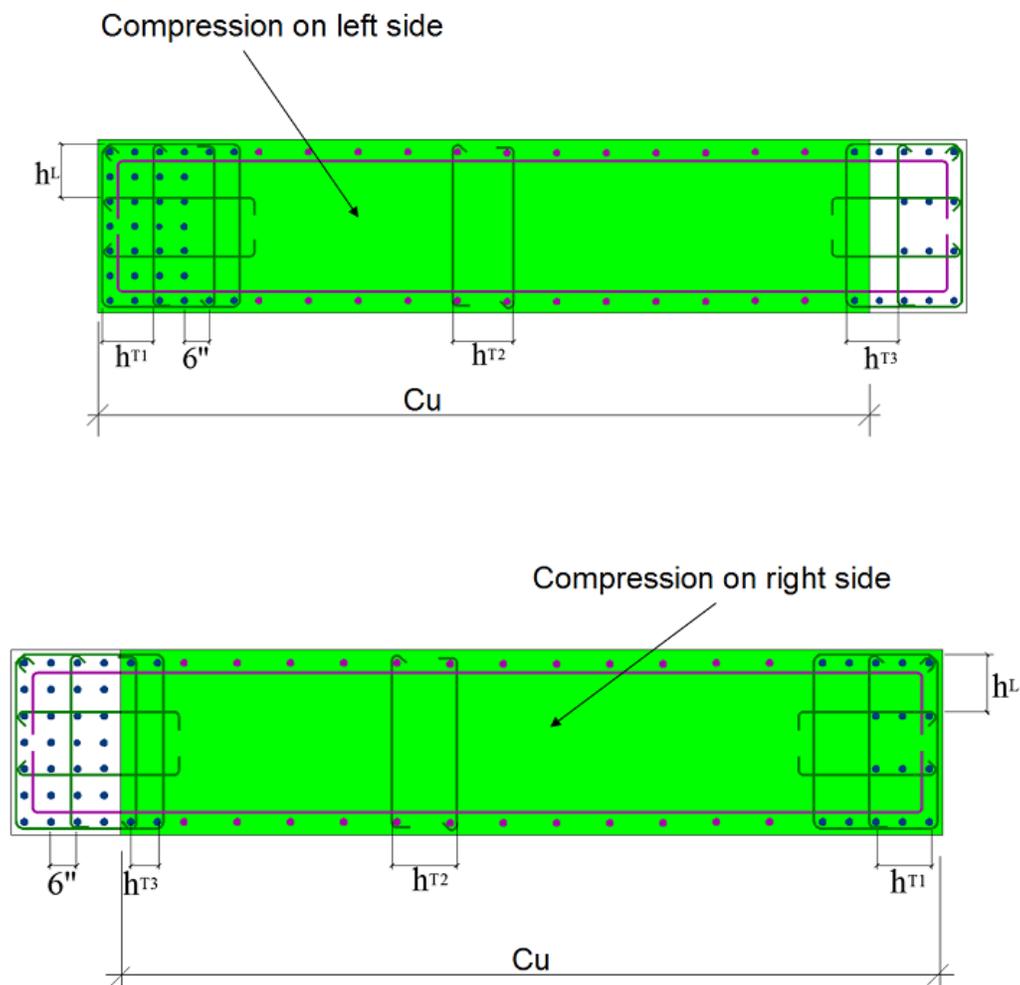


Figure 3-6 Left and Right Side Boundary Elements

The spacing parameters, h_{T1} , h_{T3} and h_L , are linked to the input fields contained in the **Design** tab. The value h_{T2} is automatically calculated (non-input). Similarly the number of legs associated with h_{T1} , and h_L are linked with input fields in the **Design** tab. The

number of legs associated with h_{T2} and h_{T3} are input fields for investigation, and calculated automatically (output fields) in auto-design mode.

The following field entry handling apply to the **Boundary Element** dialogue window:

- **Tie size** – Rebar size used for tie. Auto-calculated
- **Smax** – Maximum tie spacing. Auto-calculated
- **@ spacing** – Tie spacing increment. Input for investigation and output for Auto-design
- **Boundary code** – Output only
- **Ld** – Development length for vertical bars. Output only
- **Ldh** – Development length for horizontal bars. Output only
- **Lz,req, Lz,prov** – Required and provided confinement lengths. Output only

In Auto-design mode, the program will automatically calculate all fields, based on the input specified in "Design" tab, and the selected method. In investigation mode, the user is required to manually enter the input values, in particular number of tie legs.

The following caveats apply to the boundary element design and investigation modes.

- Zone reinforcement is calculated per ACI 318-11 for two cases: 1) When strain is more than 0.003, and 2) When stress > 0.2 f'c. The user defines the method in **General Settings**.
- For Strain > 0.003 the curvature has to be calculated based on top nonlinear lateral displacement of the wall due to seismic load. The user is required to manually input D_u/H_w for this calculation.
- The load case for "EQ" must be set to 0 or 1 for non-seismic loading and seismic loading.
- The definition of the horizontal dimensions depend on the compression side. The parameter h_{T1} is on the right for the right zone and on the left for the left zone.
- Ties are placed every single bar when horizontal distances are defined.
- Rebar placement is assumed to be filled from the end face towards inside of the wall. Maximum number of bars at each end is Curtains x n_{face}

ADAPT-ShearWall 2016 - [D:\...R>Main\BuilderModules\WallDesign\Input Data EQ_L49 E MEZZP-E2-1-debug.AWL]

File Edit Options Help

Calculate
Auto Design
Min. Rebar Horz.
Min. Rebar Vert.
Set Distance
Update Loads
Boundary Check

General Settings Loads Design P-M interaction **Boundary Elements**

Boundary Check Method
Method: Stress > 0.2 fc Du/Hw: 0.02

Left Zone

| Ties Spacing | Legs | Tie Size | @ (Spacing) | Smax |
|------------------|------|----------|-------------|------|
| hT1: 6 | 2 | 4 | 8 | 8 |
| hT2: 10.15344375 | 2 | 4 | 8 | 8 |
| hT3: 6 | 0 | 4 | 0 | 0 |
| hL: 7.25 | 3 | 4 | 8 | 8 |

Boundary: 2 Ld: 13.2662568841 Lz,req: 20.7336306855 Design Status: O.K.
Ldh: 6 Lz,prov: 28.0568875

Right Zone

| Ties Spacing | Legs | Tie Size | @ (Spacing) | Smax |
|------------------|------|----------|-------------|------|
| hT1: 6 | 2 | 3 | 2 | 2 |
| hT2: 10.15344375 | 2 | 3 | 3 | 3 |
| hT3: 6 | 0 | 4 | 0 | 0 |
| hL: 7.25 | 3 | 3 | 2 | 2 |

Boundary: 3 Ld: 13.2662568841 Lz,req: 20.7336306855 Design Status: O.K.
Ldh: 6 Lz,prov: 27.9318875

Status Code: American-ACI318 (2011) Units: American 5/16/2016 4:13 PM

Figure 3-7 Boundary Element Input Window

4 Shear Wall Design Per ACI-318

This chapter summarizes the design code requirements and design procedure of regular and special shear walls based on ACI 318 and the algorithm used for ADAPT Wall Designer (AWD).

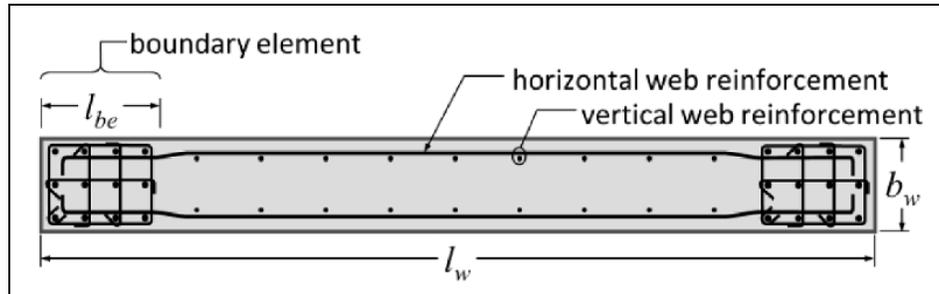


Figure 4-1 Reinforcement Schematic for Special Structural Wall

The above schematic presents typical reinforcement of a special structural wall of rectangular cross section. As a minimum, a special structural wall must contain distributed web (panel) reinforcement in both horizontal and vertical directions. A special structural wall also includes vertical reinforcement concentrated at the wall boundaries to provide additional resistance to moment and axial force. Longitudinal reinforcement is enclosed in transverse reinforcement to confine the concrete and restrain longitudinal rebar buckling.

A boundary element is a portion of a structural wall edge or opening that is strengthened by both longitudinal and transverse reinforcement. Where combined seismic and gravity loading results in high compressive demands on the edge, ACI 318 requires usage of a special boundary element. These elements incorporate closely spaced transverse reinforcement enclosing the vertical boundary bars, increasing compressive strain capacity of core concrete and restraining longitudinal rebar buckling.

4.1 Minimum Reinforcement

For Regular structural walls, calculation of minimum distributed web reinforcement is governed by ACI 318-11 section 11.4.6.3,

11.4.6.3 — Where shear reinforcement is required by 11.4.6.1 or for strength and where 11.5.1 allows torsion to be neglected, $A_{v,min}$ for prestressed (except as provided in 11.4.6.4) and nonprestressed members shall be computed by

$$A_{v,min} = 0.75 \sqrt{f'_c} \frac{b_w s}{f_{yt}} \quad (11-13)$$

but shall not be less than $(50b_w s)/f_{yt}$.

and ACI 318-11 section 14.3.3

14.3.3 — Minimum ratio of horizontal reinforcement area to gross concrete area, ρ_t , shall be:

- (a) 0.0020 for deformed bars not larger than No. 5 with f_y not less than 60,000 psi; or
- (b) 0.0025 for other deformed bars; or
- (c) 0.0020 for welded wire reinforcement not larger than W31 or D31.

Minimum vertical reinforcement is also governed by ACI 318-11 section 14.3.2:

14.3.2 — Minimum ratio of vertical reinforcement area to gross concrete area, ρ_v , shall be:

- (a) 0.0012 for deformed bars not larger than No. 5 with f_y not less than 60,000 psi; or
- (b) 0.0015 for other deformed bars; or
- (c) 0.0012 for welded wire reinforcement not larger than W31 or D31.

For special structural walls, calculation of minimum distributed web reinforcement is also governed by ACI 318-11 section 21.9.2.1. The distributed web reinforcement ratios, ρ_v for vertical reinforcement and ρ_t for horizontal reinforcement, must be at least 0.0025, except that ρ_v and ρ_t are permitted to be reduced if $V_u \leq A_{cv}\lambda V_f'c$. Reinforcement spacing each way is not to exceed 18 inches. At least two curtains (layers) of reinforcement are required if $V_u > 2A_{cv}\lambda V_f'c$.

21.9.2.1 — The distributed web reinforcement ratios, ρ_v and ρ_t , for structural walls shall not be less than 0.0025, except that if V_u does not exceed $A_{cv}\lambda\sqrt{f_c'}$, ρ_v and ρ_t shall be permitted to be reduced to the values required in 14.3. Reinforcement spacing each way in structural walls shall not exceed 18 in. Reinforcement contributing to V_n shall be continuous and shall be distributed across the shear plane.

The provision ACI 318 section 16.4.2 defines minimum amounts of vertical and horizontal reinforcement for the walls.

16.4.2 — For precast, nonprestressed walls the reinforcement shall be designed in accordance with the provisions of Chapters 10 or 14, except that the area of horizontal and vertical reinforcement each shall be not less than $0.001A_g$, where A_g is the gross cross-sectional area of the wall panel. Spacing of reinforcement shall not exceed 5 times the wall thickness nor 30 in. for interior walls nor 18 in. for exterior walls.

4.2 Wall Shear Strength Design

The design shear strength of a wall is equal the sum of concrete shear strength plus the reinforcement shear strength as follows:

$$V_u \leq \phi V_c + \phi V_s$$

The nominal shear strength of any section of the wall cannot exceed the requirements of ACI 318-11 section 11.9.3 & 11.9.4

11.9.3 — V_n at any horizontal section for shear in plane of wall shall not be taken greater than $10\sqrt{f'_c} h d$, where h is thickness of wall, and d is defined in 11.9.4.

11.9.4 — For design for horizontal shear forces in plane of wall, d shall be taken equal to $0.8\ell_w$. A larger value of d , equal to the distance from extreme compression fiber to center of force of all reinforcement in tension, shall be permitted to be used when determined by a strain compatibility analysis.

The value of shear strength provided by concrete V_c cannot exceed the requirements of ACI 318-11 section 11.2.1.1:

11.2.1.1 — For members subject to shear and flexure only,

$$V_c = 2\lambda\sqrt{f'_c} b_w d \quad (11-3)$$

If demand shear V_u exceeds ϕV_c , design of shear reinforcement for walls is governed by requirements of ACI 318-11, section 11.9.9.

The calculation of shear web reinforcement is performed according to ACI 318-11 section 11.4.7.2:

11.4.7.2 — Where shear reinforcement perpendicular to axis of member is used,

$$V_s = \frac{A_v f_y t d}{s} \quad (11-15)$$

where A_v is the area of shear reinforcement within spacing s .

or by similar requirement of section 11.9.9.1:

11.9.9.1 — Where V_u exceeds ϕV_c , horizontal shear reinforcement shall be provided to satisfy Eq. (11-1) and (11-2), where V_s shall be computed by

$$V_s = \frac{A_v f_y d}{s} \quad (11-29)$$

where A_v is area of horizontal shear reinforcement within spacing s , and d is determined in accordance with 11.9.4. Vertical shear reinforcement shall be provided in accordance with 11.9.9.4.

The spacing of vertical shear reinforcement is governed by section 11.9.9.5:

11.9.9.5 — Spacing of vertical shear reinforcement shall not exceed the smallest of $\ell_w/3$, $3h$, and 18 in., where ℓ_w is the overall length of the wall.

4.3 Wall P-M Strength Design

The strength calculations for structural walls resisting combined flexure and axial force directly are similar to the calculations for concrete columns in accordance with requirements of ACI 318-11 chapter 10.

Specifically, the calculations assume linear strain distribution, idealized stress-strain relations for concrete and reinforcement, and material strain limits per ACI 318 § 10.2 and 10.3. Boundary elements and the wall web are considered effective. Portion of vertical shear rebars which is more than required is included in moment calculations with equal spaces.

For combined flexure and axial force in a wall, the strength reduction factor ϕ is determined based on ACI 318-11 section 9.3.2.

9.3.2 — Strength reduction factor ϕ shall be as given in 9.3.2.1 through 9.3.2.7:

9.3.2.1 — Tension-controlled sections as defined in 10.3.4..... 0.90
(See also 9.3.2.7)

9.3.2.2 — Compression-controlled sections, as defined in 10.3.3:

- (a) Members with spiral reinforcement conforming to 10.9.30.75
- (b) Other reinforced members0.65

For sections in which the net tensile strain in the extreme tension steel at nominal strength, ϵ_t , is between the limits for compression-controlled and tension-controlled sections, ϕ shall be permitted to be linearly increased from that for compression-controlled sections to 0.90 as ϵ_t increases from the compression-controlled strain limit to 0.005.

For this purpose, e_t is defined as the net tensile strain in the extreme tension steel when the section reaches nominal strength ($e_{cu} = 0.003$). If $e_t \geq 0.005$, $\phi = 0.9$. If $e_t \leq f_y$ (taken as 0.002 for Grade 60), $\phi = 0.65$ for tied boundary elements or 0.75 for spiral reinforced boundary elements. The value of ϕ is interpolated for intermediate values of e_t .

The maximum nominal compression force strength is given by ACI 318-11 section 10.3.6:

10.3.6 — Design axial strength ϕP_n of compression members shall not be taken greater than $\phi P_{n,max}$, computed by Eq. (10-1) or (10-2).

10.3.6.1 — For nonprestressed members with spiral reinforcement conforming to 7.10.4 or composite members conforming to 10.13:

$$\phi P_{n,max} = 0.85\phi [0.85f'_c (A_g - A_{st}) + f_y A_{st}] \quad (10-1)$$

10.3.6.2 — For nonprestressed members with tie reinforcement conforming to 7.10.5:

$$\phi P_{n,max} = 0.80\phi [0.85f'_c (A_g - A_{st}) + f_y A_{st}] \quad (10-2)$$

The maximum nominal tension force that the wall can carry is given by ACI 318-11

$$P_{ot} = f_y A_s$$

The program uses the requirements of strain compatibility to determine the nominal axial strength and moment strength (P_n , M_n) of the wall pier. The coordinates of these points are determined by rotating linear strain line on the section of the wall pier. The maximum concrete strain is always taken as -0.003 and the maximum steel strain is varied from -0.003 to plus infinity. When the steel strain is -0.003 , the maximum compressive force in the wall pier, P_{oc} , is obtained from the strain compatibility analysis. When the steel strain is plus infinity, the maximum tensile force in the wall pier, P_{ot} , is obtained.

The compressive stress in the concrete is calculated (ACI 10.2.7.1) as follows:

$$0.85f'_c\beta_1 c_t\rho$$

The value of β_1 is determined from ACI 318-11 section 10.2.7.3

10.2.7.3 — For f'_c between 2500 and 4000 psi, β_1 shall be taken as 0.85. For f'_c above 4000 psi, β_1 shall be reduced linearly at a rate of 0.05 for each 1000 psi of strength in excess of 4000 psi, but β_1 shall not be taken less than 0.65.

The following schematic illustrates the strains and the stresses in the wall under ULS design condition:

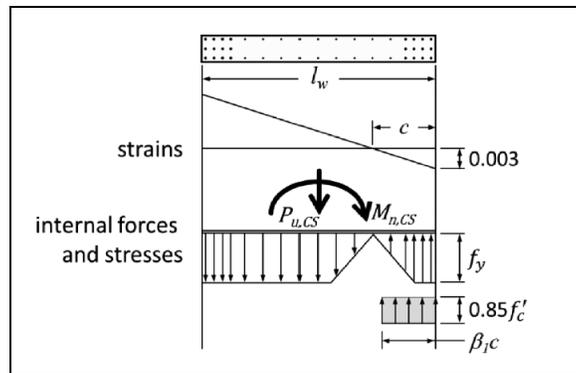


Figure 4-2 Ultimate Limit State Stress/Strain Condition in wall

The computer algorithm implemented in ADAPT Wall Designer considers loading cases, where either left or right side of the wall is in compression. The following schematics illustrate such conditions, together with relevant notation.

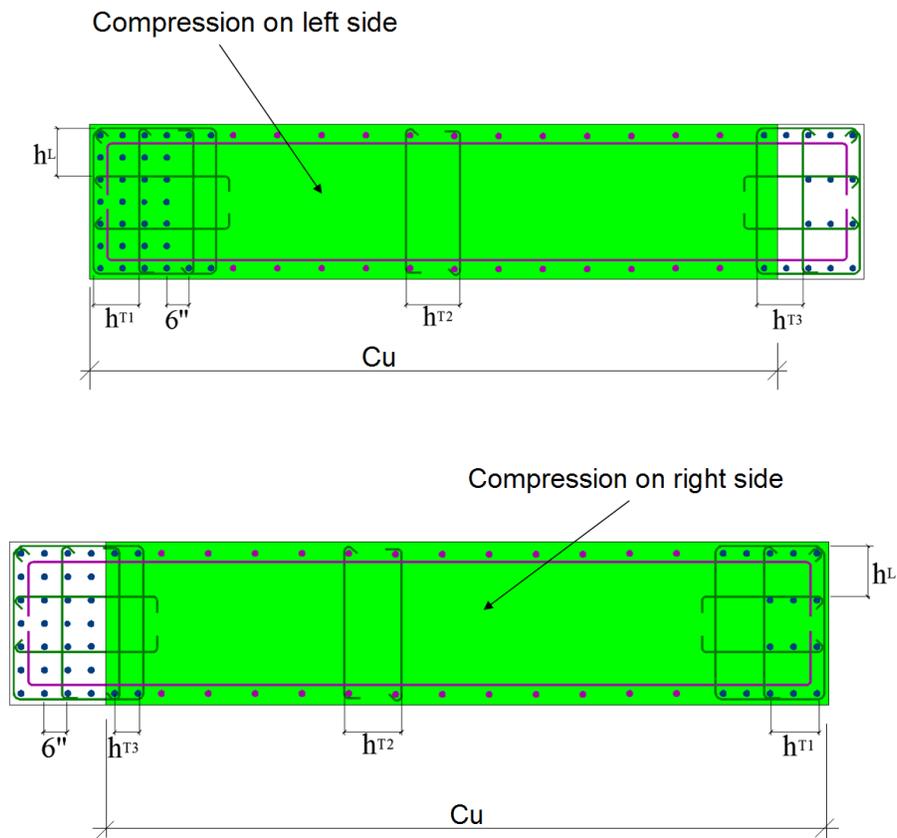


Figure 4-3 Schematic of wall zones in compression

4.4 Special Boundary Elements

ACI 318 provides two methods for determining whether special boundary elements are required. The preferred method (Method "Strain > 0.003") (ACI 318 section 21.9.6.2):

21.9.6.2 — This section applies to walls or wall piers that are effectively continuous from the base of structure to top of wall and designed to have a single critical section for flexure and axial loads. Walls not satisfying these requirements shall be designed by **21.9.6.3**.

(a) Compression zones shall be reinforced with special boundary elements where

$$c \geq \frac{\ell_w}{600(\delta_u/h_w)} \quad (21-8)$$

c in Eq. (21-8) corresponds to the largest neutral axis depth calculated for the factored axial force and nominal moment strength consistent with the design displacement δ_u . Ratio δ_u/h_w in Eq. (21-8) shall not be taken less than 0.007;

(b) Where special boundary elements are required by 21.9.6.2(a), the special boundary element reinforcement shall extend vertically from the critical section a distance not less than the larger of l_w or $M_u/4V_u$.

The method applies to walls that are effectively continuous from base of structure to top of wall or segment and designed to have a single critical section for flexure and axial force.

To use this method, the seismic force-resisting system is first sized and then analyzed to determine the top-level design displacement du and corresponding maximum value of wall axial force Pu . The flexural compression depth c corresponding to nominal moment strength Mn,CS under axial force Pu is then calculated. If the compression zone exceeds:

$$c \geq \frac{l_w}{600 (\delta_u/h_w)} \quad (\text{ACI 318 Eq. 21-8})$$

Where h_w refers to total wall height from critical section to top of wall, then special boundary elements are required. Where special boundary elements are required by Method I, they must extend vertically above and below the critical section a distance not less than the greater of l_w and $M_u,CS/4V_u,CS$.

The second method (Method "Stress > 0.2 f_c' ") for determining if special boundary elements are required, is based on nominal compressive stress (ACI 318 section 21.9.6.3).

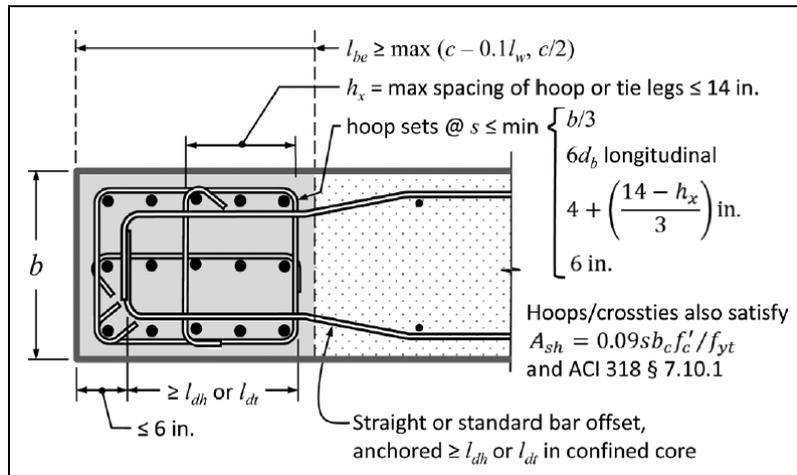
21.9.6.3 — Structural walls not designed to the provisions of 21.9.6.2 shall have special boundary elements at boundaries and edges around openings of structural walls where the maximum extreme fiber compressive stress, corresponding to load combinations including earthquake effects, E , exceeds $0.2f_c'$. The special boundary element shall be permitted to be discontinued where the calculated compressive stress is less than $0.15f_c'$. Stresses shall be calculated for the factored forces using a linearly elastic model and gross section properties. For walls with flanges, an effective flange width as defined in 21.9.5.2 shall be used.

First, the seismic force-resisting system is sized and analyzed to determine axial forces and moments under design load combinations. Using a gross-section model of the wall cross section, nominal stress at wall edges is calculated from $s = Pu/Ag + Mux/Sgx +$

M_{uy}/S_{gy} . Special boundary elements are required at an edge if nominal stress exceeds $0.2f'_c$. If a special boundary element is required, it must be continued vertically (upward and downward) until compressive stress drops below $0.15f'_c$. Method "Stress > $0.2 f_c$ " can be used for any wall. The preferred use is for irregular or discontinuous walls for which Method "Strain > 0.003" does not apply.

Where a special boundary element is required, ACI 318 section 21.9.6.4 (a) requires it to extend horizontally from the wall edge a distance not less than the greater of $c - 0.1l_w$ and $c/2$. Flexural compression depth c is calculated at nominal moment strength M_n, CS under maximum axial force P_u .

(a) The boundary element shall extend horizontally from the extreme compression fiber a distance not less than the larger of $c - 0.1l_w$ and $c/2$, where c is the largest neutral axis depth calculated for the factored axial force and nominal moment strength consistent with δ_u ;



Special boundary elements must have transverse confinement reinforcement satisfying requirements of ACI 318-11 section 21.6.4.4(b) & 7.10.5.1:

21.6.4.4 — The amount of transverse reinforcement required in (a) or (b) shall be provided unless a larger amount is required by **21.6.5**.

(b) The total cross-sectional area of rectangular hoop reinforcement, A_{sh} , shall not be less than required by Eq. (21-4) and (21-5)

$$A_{sh} = 0.3 \frac{s b_c f'_c}{f_{yt}} \left[\left(\frac{A_g}{A_{ch}} \right) - 1 \right] \quad (21-4)$$

$$A_{sh} = 0.09 \frac{s b_c f'_c}{f_{yt}} \quad (21-5)$$

7.10.5.1 — All nonprestressed bars shall be enclosed by transverse ties, at least No. 3 in size for longitudinal bars No. 10 or smaller, and at least No. 4 in size for No. 11, No. 14, No. 18, and bundled longitudinal bars. Deformed wire or welded wire reinforcement of equivalent area shall be permitted.

Spacing of transverse reinforcement shall satisfy requirements of ACI 318-11 section 21.9.6.2-4:

(c) The boundary element transverse reinforcement shall satisfy the requirements of 21.6.4.2 through 21.6.4.4, except Eq. (21-4) need not be satisfied and the transverse reinforcement spacing limit of 21.6.4.3(a) shall be one-third of the least dimension of the boundary element;

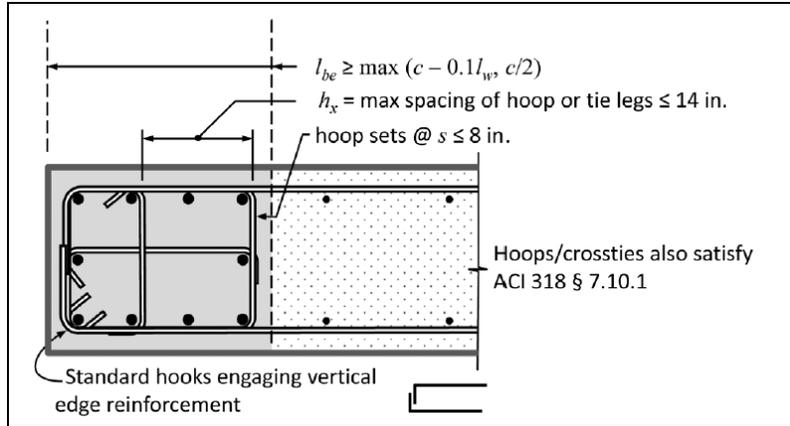
21.6.4.3 — Spacing of transverse reinforcement along the length ℓ_o of the member shall not exceed the smallest of (a), (b), and (c):

- (a) One-quarter of the minimum member dimension;
- (b) Six times the diameter of the smallest longitudinal bar; and
- (c) s_o , as defined by Eq. (21-2)

$$s_o = 4 + \left(\frac{14 - h_x}{3} \right) \quad (21-2)$$

The value of s_o shall not exceed 6 in. and need not be taken less than 4 in.

At wall boundaries where special boundary elements are not required, ACI 318 section 21.9.6.5 requires usage of ordinary boundary elements if the boundary element longitudinal reinforcement ratio $A_{s,be}/A_{g,be} > 400/f_y$, where $A_{s,be}/A_{g,be}$ is the local ratio at the wall boundary only. The schematic of ordinary boundary element is presented in the following image:



Where $A_{s,be}/A_{g,be} \leq 400/f_y$, ACI 318 section 14.3.6 permits the section to be detailed without ties enclosing the vertical reinforcement.

21.9.6.5 — Where special boundary elements are not required by 21.9.6.2 or 21.9.6.3, (a) and (b) shall be satisfied:

(a) If the longitudinal reinforcement ratio at the wall boundary is greater than $400/f_y$, boundary transverse reinforcement shall satisfy 21.6.4.2 and 21.9.6.4(a). The maximum longitudinal spacing of transverse reinforcement in the boundary shall not exceed 8 in.;

(b) Except when V_u in the plane of the wall is less than $A_{cv}\lambda\sqrt{f'_c}$, horizontal reinforcement terminating at the edges of structural walls without boundary elements shall have a standard hook engaging the edge reinforcement or the edge reinforcement shall be enclosed in U-stirrups having the same size and spacing as, and spliced to, the horizontal reinforcement.

At the interface with a footing, foundation mat, pile cap, or other support, longitudinal reinforcement of structural walls must be fully developed in tension. Development length "Ld" for vertical bars of special element anchored in footing is calculated based on ACI 318-11 section 21.2.3 & 12.2.3.

21.9.2.3 — Reinforcement in structural walls shall be developed or spliced for f_y in tension in accordance with **Chapter 12**, except:

- (a) The effective depth of the member referenced in **12.10.3** shall be permitted to be taken as $0.8\ell_w$ for walls.
- (b) The requirements of **12.11**, **12.12**, and **12.13** need not be satisfied.
- (c) At locations where yielding of longitudinal reinforcement is likely to occur as a result of lateral displacements, development lengths of longitudinal reinforcement shall be 1.25 times the values calculated for f_y in tension.
- (d) Mechanical splices of reinforcement shall conform to **21.1.6** and welded splices of reinforcement shall conform to **21.1.7**.

12.2.3 — For deformed bars or deformed wire, ℓ_d shall be

$$\ell_d = \left(\frac{3}{40} \frac{f_y}{\lambda \sqrt{f'_c}} \frac{\Psi_t \Psi_e \Psi_s}{\left(\frac{c_b + K_{tr}}{d_b} \right)} \right) d_b \quad (12-1)$$

in which the confinement term $(c_b + K_{tr})/d_b$ shall not be taken greater than 2.5, and

$$K_{tr} = \frac{40A_{tr}}{sn} \quad (12-2)$$

where n is the number of bars or wires being spliced or developed along the plane of splitting. It shall be permitted to use $K_{tr} = 0$ as a design simplification even if transverse reinforcement is present.

Development length "Ldh" for horizontal web bars anchored in special elements is calculated according to ACI 318-11 section 21.9.2.3 & 12.5.2.

12.5.2 — For deformed bars, ℓ_{dh} shall be $(0.02 \psi_e f_y / \lambda \sqrt{f'_c}) d_b$ with ψ_e taken as 1.2 for epoxy-coated reinforcement, and λ taken as 0.75 for lightweight concrete. For other cases, ψ_e and λ shall be taken as 1.0.

12.5.3 — Length ℓ_{dh} in 12.5.2 shall be permitted to be multiplied by the following applicable factors:

- (a) For No. 11 bar and smaller hooks with side cover (normal to plane of hook) not less than 2-1/2 in., and

for 90-degree hook with cover on bar extension beyond hook not less than 2 in. **0.7**

4.5 Wall Slenderness Checks

The algorithm implemented in ADAPT Wall Designer calculates the slenderness ratio of the wall as follows:

$$l_u / r$$

where:

l_u - clear story height

r - radius of gyration of the wall

Slenderness ratio is checked against the limiting condition:

$$l_u / r \leq 34$$

which is equivalent to the ACI 318 requirement:

$$\frac{k l_u}{r} \leq 34 - 12(M_1/M_2) \leq 40 \quad (10-7)$$

The calculation of radius of gyration of a wall is done using simplified formula:

$$r = 0.29 * \min(t, L_w)$$

Thin wall sections responding in flexure may be prone to out-of-plane buckling, typically at higher ductility levels. The 1997 UBC prescribes a minimum wall thickness of 1/16 the clear story height for walls that require boundary confinement:

1921.6.6.6 Shear wall boundary zone detail requirements.
 When required by Section 1921.6.6.1 through 1921.6.6.5, boundary zones shall meet the following:

1. Dimensional requirements.
 - 1.1 All portions of the boundary zones shall have a thickness of $l_w/16$ or greater.

The algorithm implemented in ADAPT Wall Designer checks the condition:

$$l_u / 16 \leq t$$

where:

t - wall thickness

l_u - the length which is an input parameter, should be is taken as the smaller of:

- The clear story height between floors bracing the wall in the out-of-plane direction, and
- $2.5l_p$ for single-curtain walls and walls with ρ greater than 200 / fye, or $2.0l_p$ for two-curtain walls with ρ less than or equal to 200 / fye.
- ρ = Local reinforcement ratio in boundary region of wall.

4.6 Wall Zone-less Design

The designs (investigation and auto-design) of ordinary walls can be performed in two possible modes:

- Including the flexural zone rebar at wall ends.
- Excluding the flexural zone rebar at wall ends (zone-less design).

Zone-less design is controlled by a switch "ZoneLessDesign". This mode of operation is pertaining only to ordinary walls without special boundary elements. If special zones are selected, the zone-less design selection will be ignored.

If zone-less mode is selected, the program will ignore the input pertaining to the flexural zone rebar, and assume that the number of zone bars ("BarCount_Left", "BarCount_Right") is equal zero. In such case, the program will check or design the walls flexural capacity (P-M Interaction check) assuming that the panel vertical shear rebar are distributed over the entire length of the wall and it fully participates in flexural capacity.

The input parameters (AWL file) for such models should be set as follows:

```
"ZoneLessDesign" 1
```

```
"BarCount_Left" 0
```

```
"BarCount_Right" 0
```

In the case where the program is run in investigation (calculate) mode the capacity of the wall based on the assumed panel rebars will be code-checked.

In case program is run in auto-design mode, the design for shear will be followed for iterative design for flexure, where the amount of panel rebar and bar sizes will be increased to satisfy the flexural demand. If program is unable to satisfy the

requirements for flexural capacity using distributed panel reinforcement, the auto-design calculations will attempt to switch to design including zone reinforcement.

The operation of the auto-design algorithm including the zone-less designs can be presented by the following pseudo-code:

- Design vertical panel rebar to satisfy the shear requirements.
- Test if boundary zones are required/selected and if so go to (6).
- Test if program is supposed to try to design using panel rebar only. If YES go to next step (4), if NO go to step (6).
- Test if selected vertical panel shear rebar satisfy flexural requirements, and if so stop (exit).
- Try to adjust vertical panel rebar (bar size spacing) to satisfy the flexural requirements (PM interaction). If satisfied stop (exit).
- Design for flexure using the zone bars.
- Design for boundary zones if required.

4.7 Utilization Factors

The calculation of utilization factors is performed similarly to the approach used in the S-CONCRETE program for use in the design of columns and walls within ADAPT-Builder. The following formulas (American Standards) are used for calculation of axial and flexural utilization ratios:

☒ N vs M Utilization

For load cases that fall within the failure envelope, axial load and moment utilization is computed as follows:

American Standards

$$\text{Utilization} = \frac{M_u}{\phi M_n} \text{ or } \frac{N_u}{N_{r,max}} \text{ (for } N_u \leq 0) \text{ or } \frac{N_u}{T_{r,max}} \text{ (for } N_u > 0)$$

whichever is greater

British and Singapore Standards

$$\text{Utilization} = \frac{M}{M_u} \text{ or } \frac{N}{N_{r,max}} \text{ (for } N \leq 0) \text{ or } \frac{N}{T_{r,max}} \text{ (for } N > 0)$$

whichever is greater

Canadian Standards

$$\text{Utilization} = \frac{M_f}{M_r} \text{ or } \frac{N_f}{N_{r,max}} \text{ (for } N_f \leq 0) \text{ or } \frac{N_f}{T_{r,max}} \text{ (for } N_f > 0)$$

whichever is greater

| | | | |
|-------|----------------------|---|--|
| where | M_u, M, M_f | = | Factored Bending Moment Applied |
| | $\phi M_n, M_n, M_r$ | = | Moment Capacity or Moment Resistance evaluated at the applied axial load N_u, N, N_f |
| | N_u, N, N_f | = | Factored Axial Load Applied |
| | $N_{r,max}$ | = | Axial Load Capacity in Compression |
| | $T_{r,max}$ | = | Axial Load Capacity in Tension |

Axial utilization is the ratio of the ultimate applied axial load P_u divided by axial capacity of the section $\phi * P_n$.

Moment utilization is the ratio of ultimate applied moment M_u divided by the moment capacity $\phi * M_n$ evaluated at the level of applied axial load P_u .

The calculations of utilization ratios for shear are performed using the following formula:

$$\text{Utilization} = V_u / (\phi * V_n), \text{ where } V_n = V_c + V_s.$$

The program selects maximum values from each load case under consideration. The governing load case number is also reported for each of these.

Literature Sources

1. Building Code Requirements for Structural Concrete (ACI 318-11) and Commentary.
2. Design of Reinforced Concrete 9th Edition, Jack C. McCormac. Chapter 18.6 - ACI Provisions for shear walls.
3. Seismic Design of Cast-in-Place Concrete Special Structural Walls and Coupling Beams. A Guide for Practicing Engineers. NEHRP Seismic Design Technical Brief No. 6
4. Evaluation of Earthquake Damaged Concrete and Masonry Wall Buildings. FEMA 306.