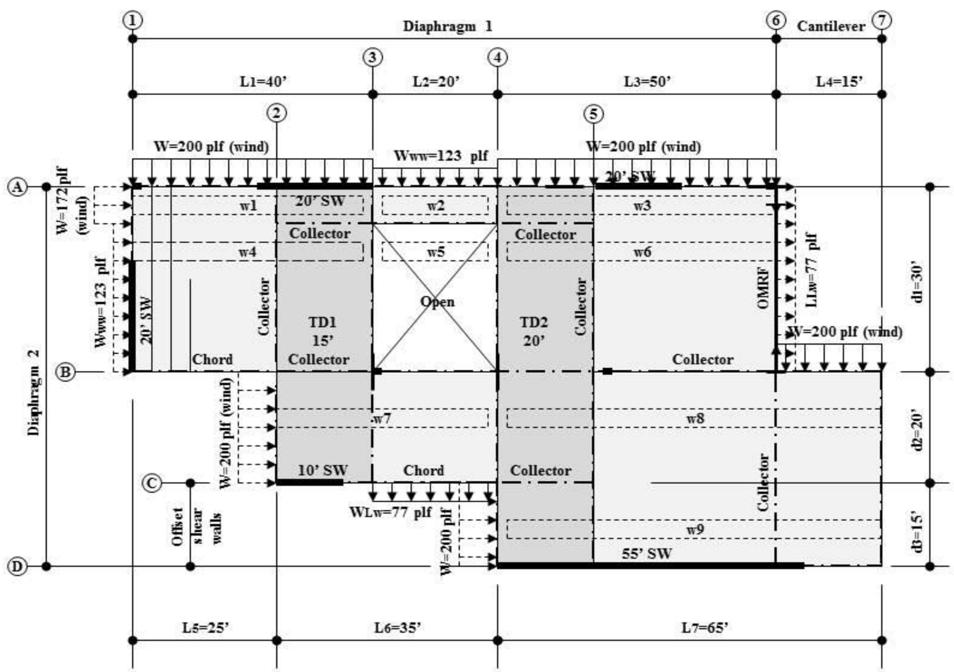
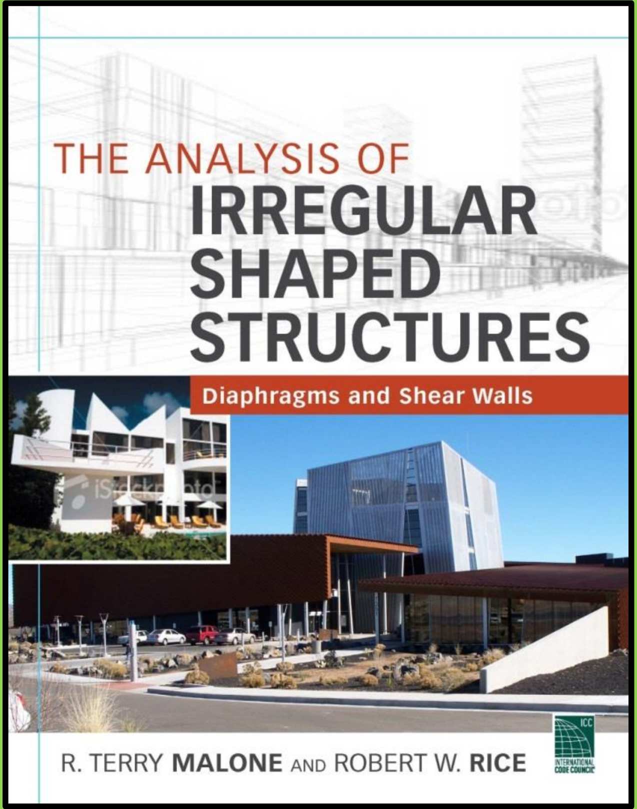
WoodWorks

Advanced Diaphragm Analysis-Workshop



Example-Complex Diagram

Presentation Based On:



Presentation updated to 2015 IBC, ASCE 7-10 2015 SDPWS

By: R. Terry Malone, PE, SE

Senior Technical Director

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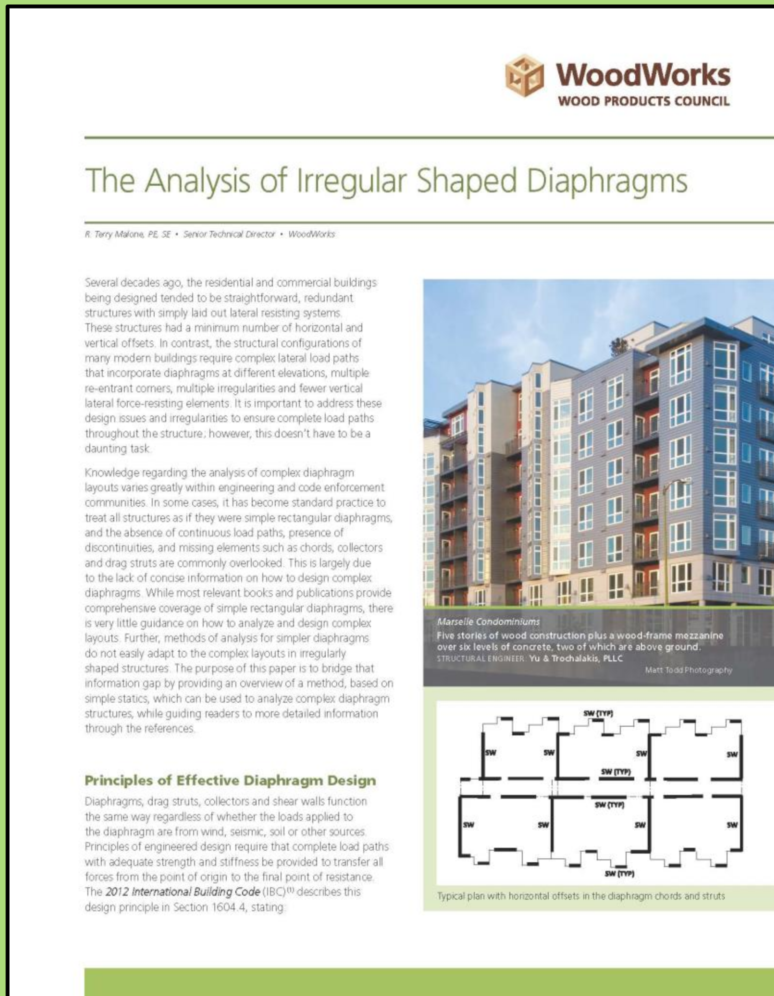
Complete Example with narrative and calculations



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The Analysis of Irregular Shaped Diaphragms

R. Terry Malone, PE, SE • Senior Technical Director • WoodWorks

Several decades ago, the residential and commercial buildings being designed tended to be straightforward, redundant structures with simply laid out lateral resisting systems. These structures had a minimum number of horizontal and vertical offsets. In contrast, the structural configurations of many modern buildings require complex lateral load paths that incorporate diaphragms at different elevations, multiple re-entrant corners, multiple irregularities and fewer vertical lateral force-resisting elements. It is important to address these design issues and irregularities to ensure complete load paths throughout the structure; however, this doesn't have to be a daunting task.

Knowledge regarding the analysis of complex diaphragm layouts varies greatly within engineering and code enforcement communities. In some cases, it has become standard practice to treat all structures as if they were simple rectangular diaphragms, and the absence of continuous load paths, presence of discontinuities, and missing elements such as chords, collectors and drag struts are commonly overlooked. This is largely due to the lack of concise information on how to design complex diaphragms. While most relevant books and publications provide comprehensive coverage of simple rectangular diaphragms, there is very little guidance on how to analyze and design complex layouts. Further, methods of analysis for simpler diaphragms do not easily adapt to the complex layouts in irregularly shaped structures. The purpose of this paper is to bridge that information gap by providing an overview of a method, based on simple statics, which can be used to analyze complex diaphragm structures, while guiding readers to more detailed information through the references.

Principles of Effective Diaphragm Design

Diaphragms, drag struts, collectors and shear walls function the same way regardless of whether the loads applied to the diaphragm are from wind, seismic, soil or other sources. Principles of engineered design require that complete load paths with adequate strength and stiffness be provided to transfer all forces from the point of origin to the final point of resistance. The *2012 International Building Code* (IBC)[1] describes this design principle in Section 1604.4, stating:

Marselle Condominiums
Five stories of wood construction plus a wood-frame mezzanine over six levels of concrete, two of which are above ground.
STRUCTURAL ENGINEER: Yu & Trochalakis, PLLC
Matt Todd Photography

Typical plan with horizontal offsets in the diaphragm chords and struts

<u>Download Process:</u>

- **WoodWorks.org website**
- **Publications-Media tab**
- **Wood Solutions Papers**

http://www.woodworks.org/publications-media/solution-papers/

http://www.woodworks.org/wp-content/uploads/Irregular-Diaphragms_Paper1.pdf

Course Description

This presentation will provide a review of a method of analysis that can be used to address irregularities that commonly occur in todays structures. Topics will include:

- **Diaphragms with horizontal offsets**
- **In-plane and out-of-plane offset shear walls**
- **Diaphragms with openings**
- **Tall shear walls**

Learning Objectives

- **Basic Information**

  Discuss boundary elements, complete lateral load paths, diaphragm flexibility and review an analytical method used for solving complex diaphragms and shear walls.

- **Diaphragms With Horizontal Offset**

  Learn how to analyze a diaphragm with a horizontal offset and how to transfer forces across areas of discontinuity.

- **In-plane and Out-of-plane Offset Shear Walls**

  Learn how to analyze in-plane and out-of plane offset shear walls.

- **Diaphragms With Openings**

  Learn how to analyze a diaphragm with an interior opening and opening at the support wall line, which creates a discontinuity in the diaphragm web.

Presentation Assumptions

Assumptions:

- Loads to diaphragms and shear walls
  - Strength level or allowable stress design
  - Wind or seismic forces.
- The loads are already factored for the appropriate load combinations.

Code and Standards:

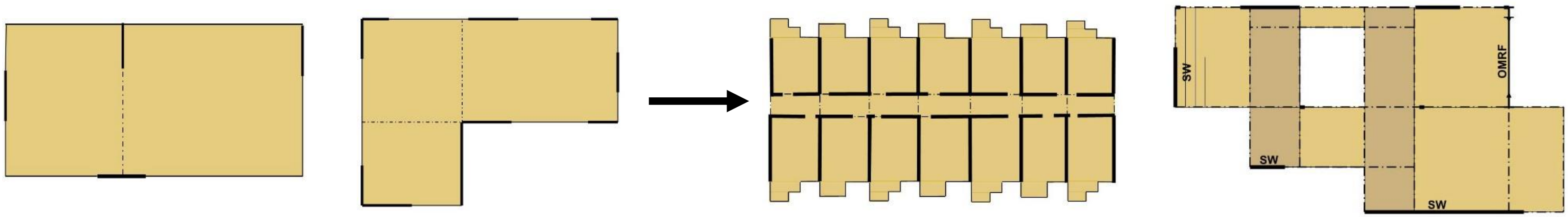
- ASCE 7-10 "Minimum Design Loads for Buildings and Other Structures"
- 2015 IBC
- 2015 SDPWS (Spid-wiz)-"Special Design Provisions for Wind and Seismic"

Analysis and Design references:

- → The Analysis of Irregular Shaped Structures: Diaphragms and Shear Walls-Malone, Rice
- Woodworks-The Analysis of Irregular Shaped Diaphragms (paper)
- → NEHRP (NIST) Seismic Design Technical Brief No. 10-Seismic Design of Wood Light-Frame Structural Diaphragm Systems: A Guide for Practicing Engineers
- SEAOC Seismic Design Manual, Volume 2
- Design of Wood Structures- Breyer, Fridley, Pollock, Cobeen
- Wood Engineering and Construction Handbook-Faherty, Williamson
- Guide to the Design of Diaphragms, Chords and Collectors-NCSEA

Evolution to Complex Buildings

- **Simple structures** **Complex structures**



- **The method of analysis is:**
  - **Can be used for all construction types.**
  - **Straight forward and simple to use. "A rational method of analysis based on simple statics !"**
  - **Well Documented over several decades**

- **Today's presentation focuses on:**
  - **Developing continuous load paths across areas of discontinuities.**
  - **<u>Flexible</u> wood sheathed or un-topped steel deck diaphragms. Can also be used for semi-rigid diaphragms.**

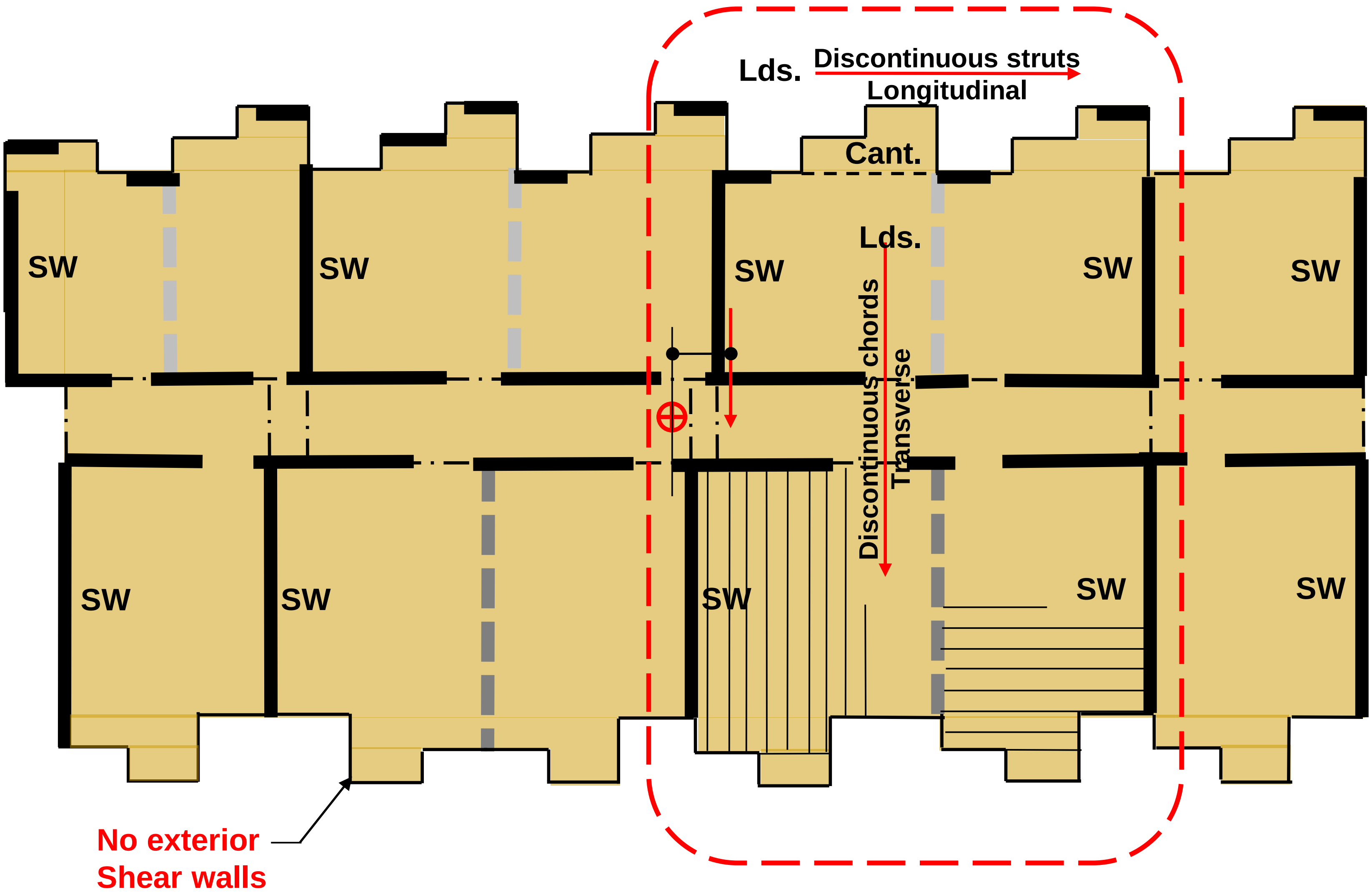
Wood diaphragms are well suited for these shapes as they can be easily adapted to the building shape and are cost effective.

Mid-rise Multi-family

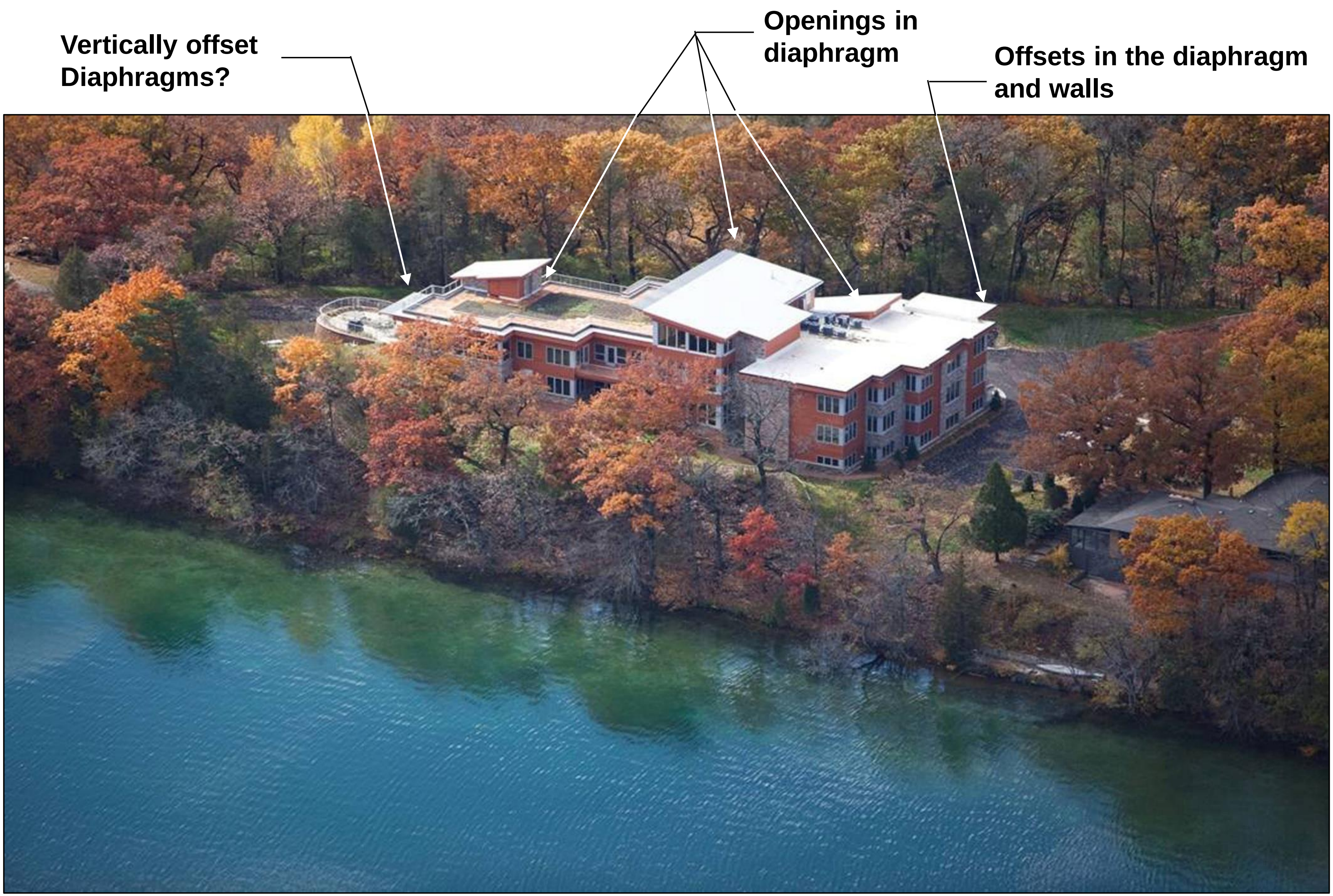
Marselle Condominiums
Structural Engineer engineer: Yu & Trochalakis, PLLC
Photographer: Matt Todd Photographer

5 stories of wood over 6 stories concrete (podium) 2 above grade

Mid-rise Multi-family



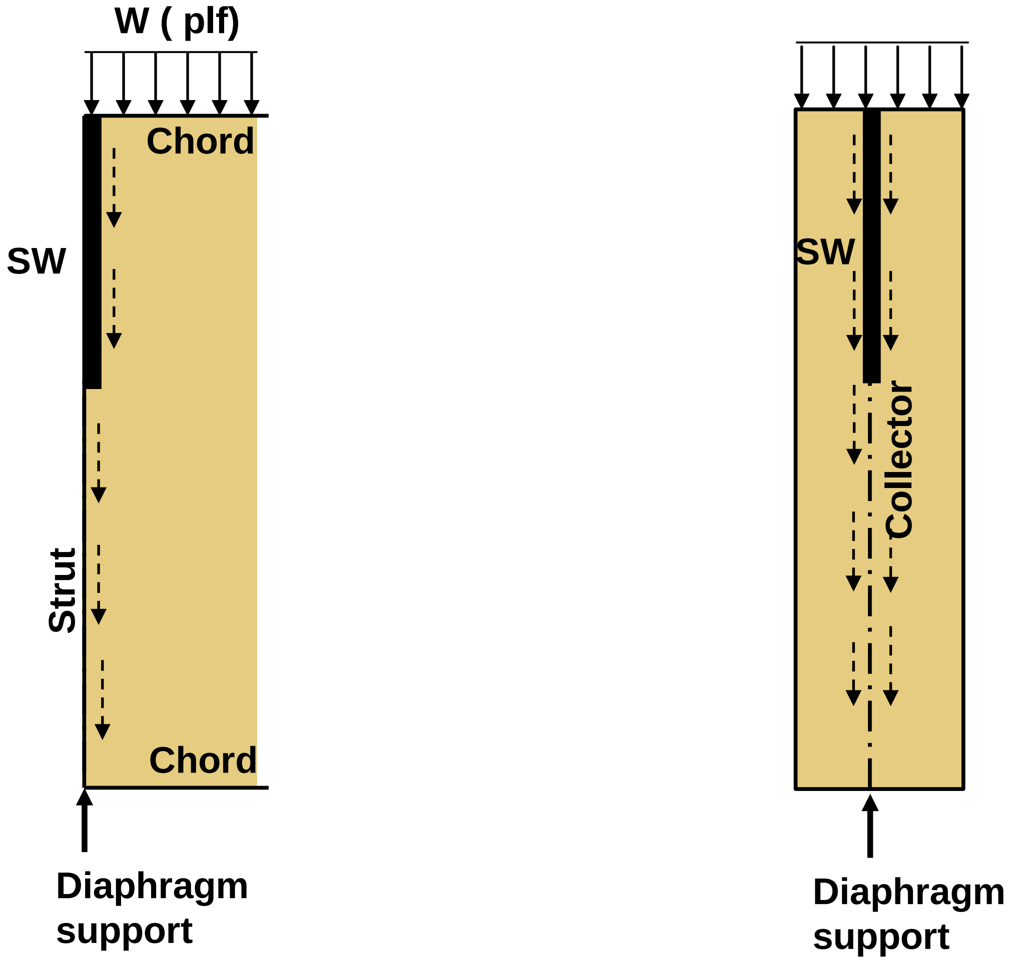
Flexible, semi-rigid, or rigid???



Harrington Recovery Center
Structural engineer: Pujara Wirth Torke, Inc.
Photographer: Curtis Walz

Basic Information

- **Boundary Elements**
- Complete Load Paths
- Diaphragm Flexibility
- Method of Analysis



<u>Strut</u>- receives shears from one side only*.
<u>Collector</u>- receives shears from both sides.

***[Drag struts and collectors are synonymous in ASCE7]**

Struts, Collectors, and Chords- (my) Terminology

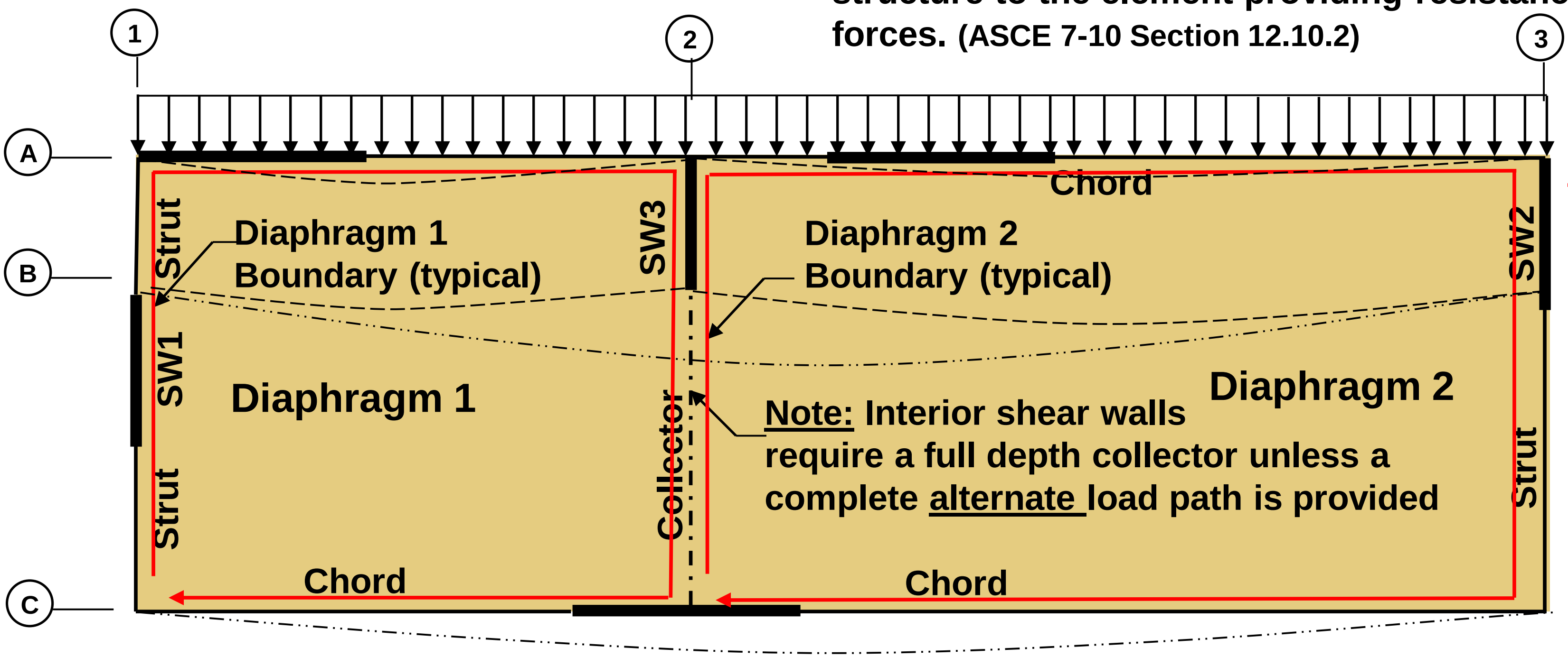
Diaphragm Boundary Elements

Fundamental Principles:
A shear wall is a location where diaphragm forces are resisted (supported), and therefore defines a diaphragm boundary location.

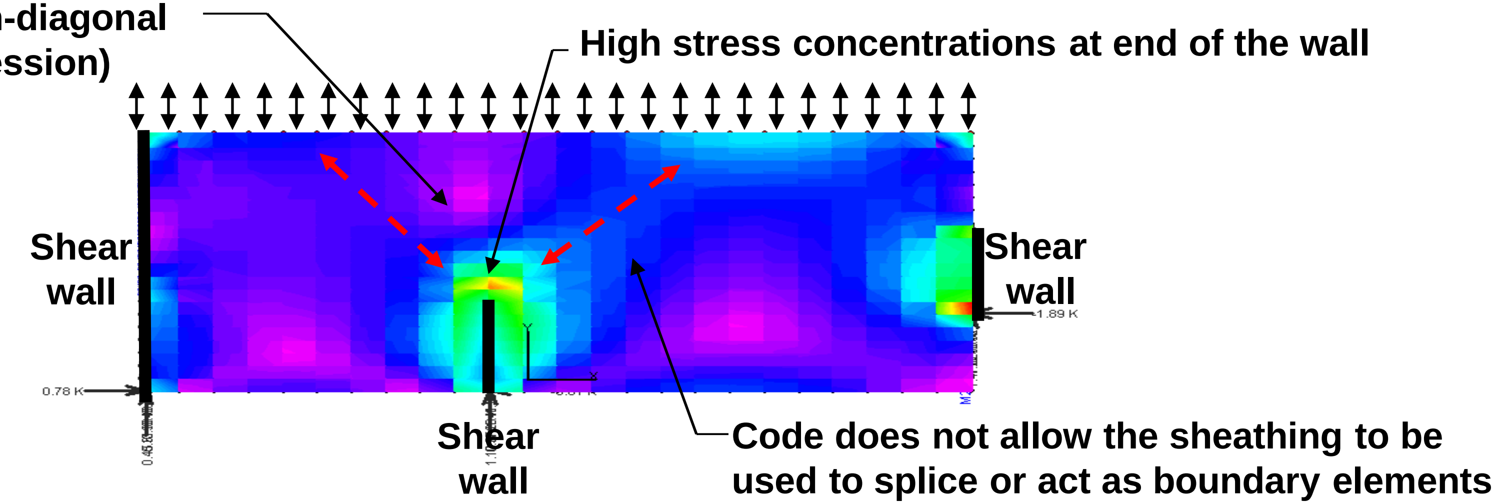
Note: All edges of a diaphragm shall be supported by a boundary element. (ASCE 7-10 Section 11.2)

- **Diaphragm Boundary Elements:**
  - Chords, drag struts, collectors, Shear walls, frames
  - Boundary member locations:
    - Diaphragm and shear wall perimeters
    - Interior openings
    - Areas of discontinuity
    - Re-entrant corners.
- Diaphragm and shear wall sheathing shall not be used to splice boundary elements. (SDPWS 4.1.4)
- Collector elements shall be provided that are capable of transferring forces originating in other portions of the structure to the element providing resistance to those forces. (ASCE 7-10 Section 12.10.2)

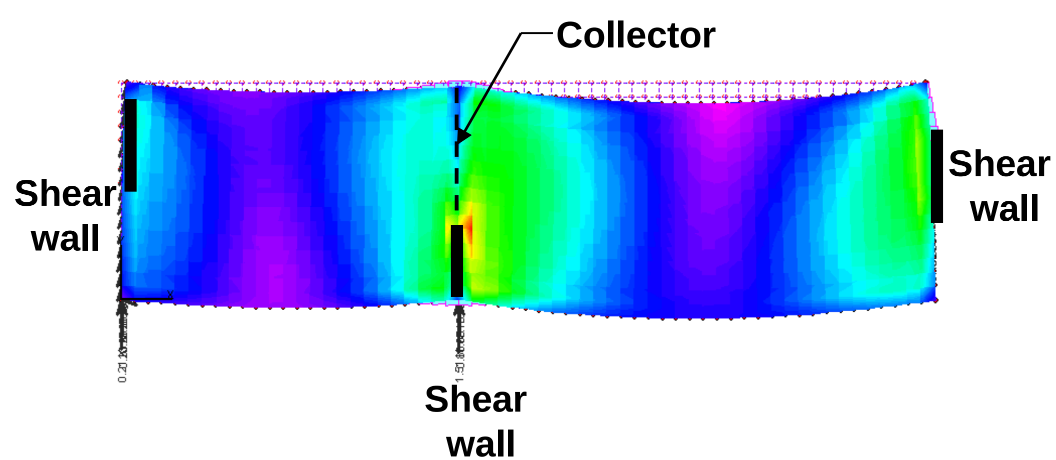
Required for Seismic and wind



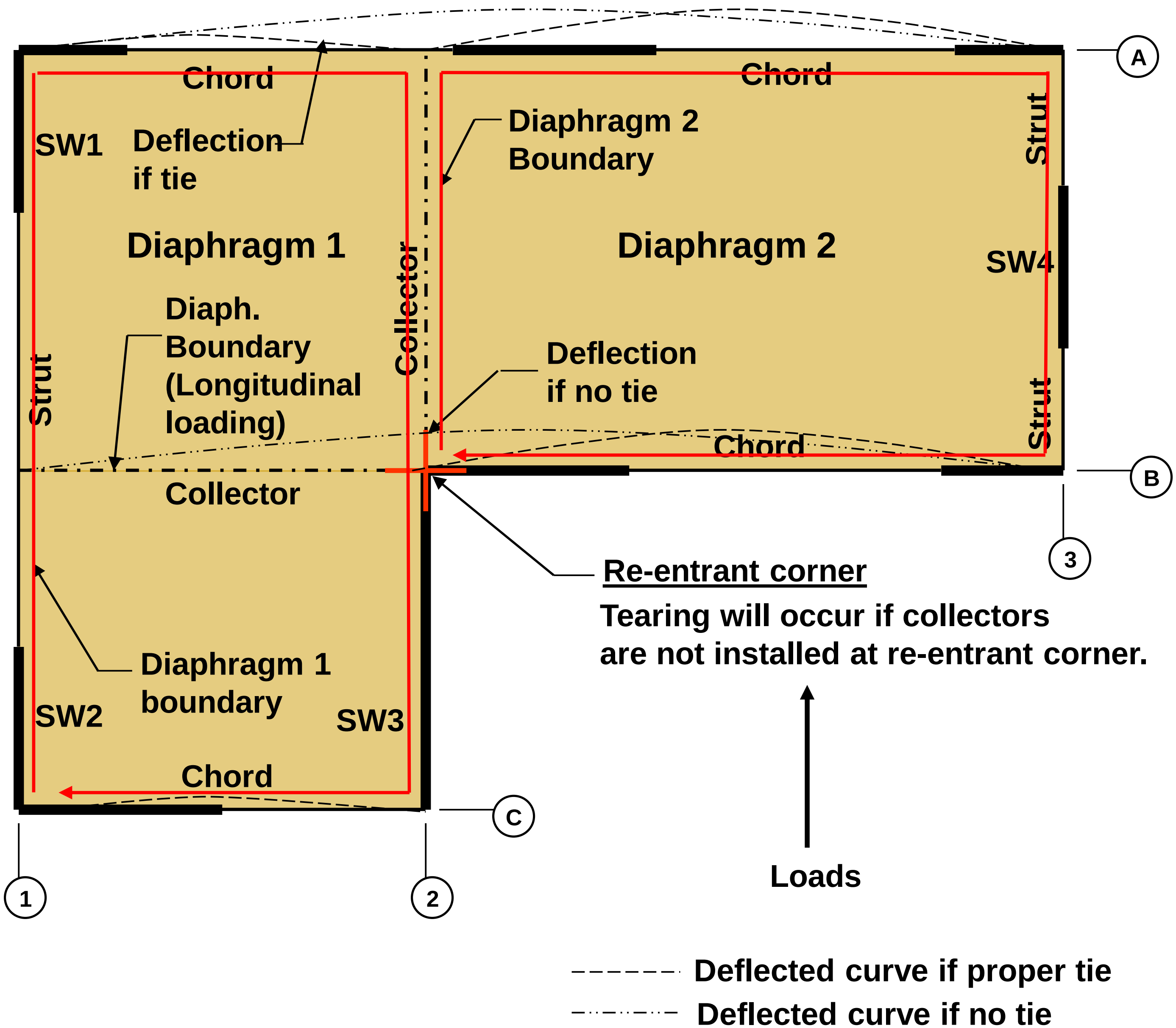
Note:
Diaphragm sections act as notched beams (shear distribution-diagonal tension or compression)



Shear Distribution if No Collector



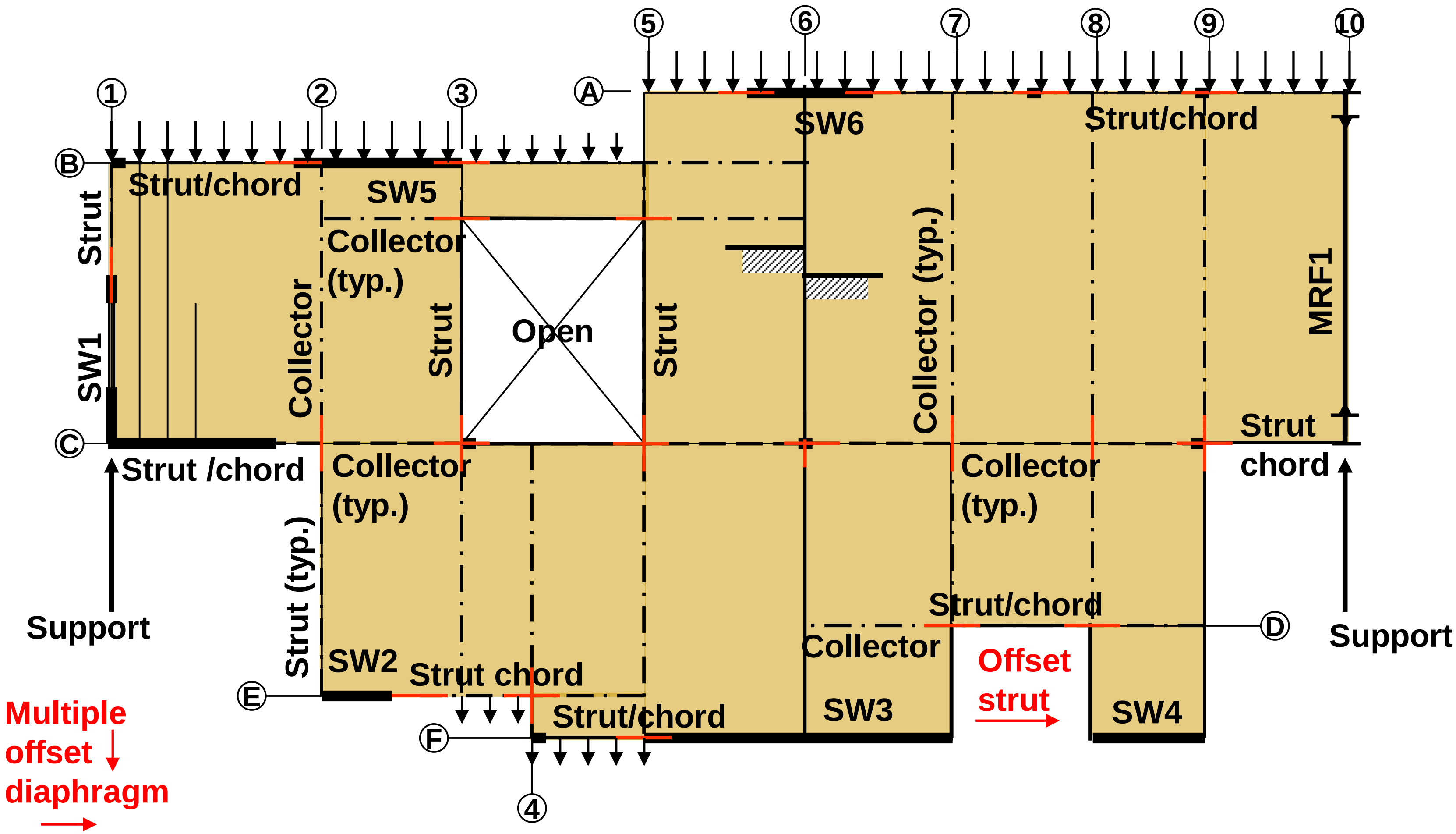
Shear Distribution if Continuous Collector



Boundary Elements "L" Shaped Buildings-Transverse Loading

Basic Information

- Boundary Elements
- **Complete Load Paths**
- Diaphragm Flexibility
- Method of Analysis

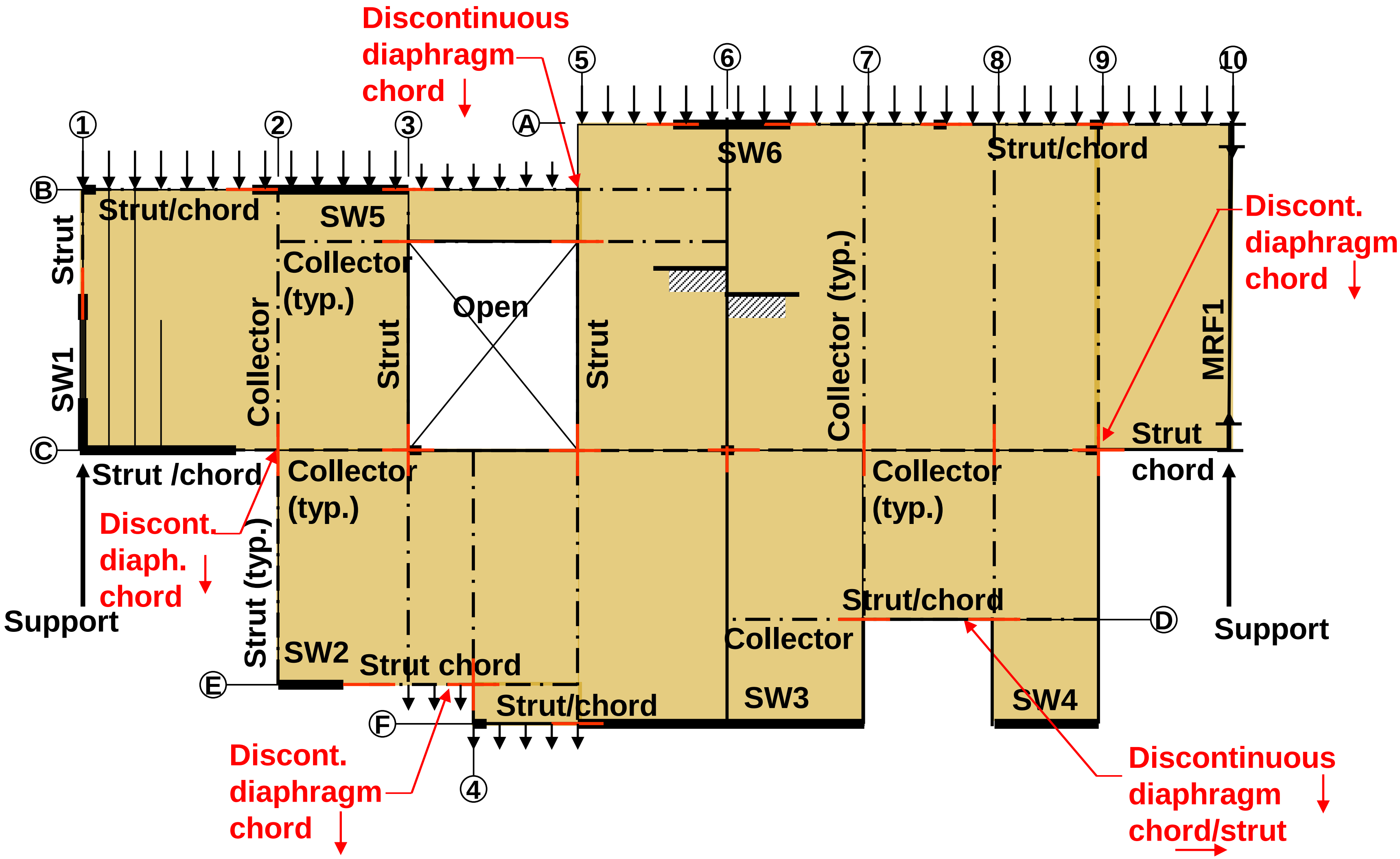


Analysis: ASCE7-10 Sections:

- 1.3.1.3.1-Design shall be based on a rational analysis
- 12.10.1-At diaphragm discontinuities such as openings and re-entrant corners, the design shall assure that the dissipation or transfer of edge (chord) forces combined with other forces in the diaphragm is within shear and tension capacity of the diaphragm.

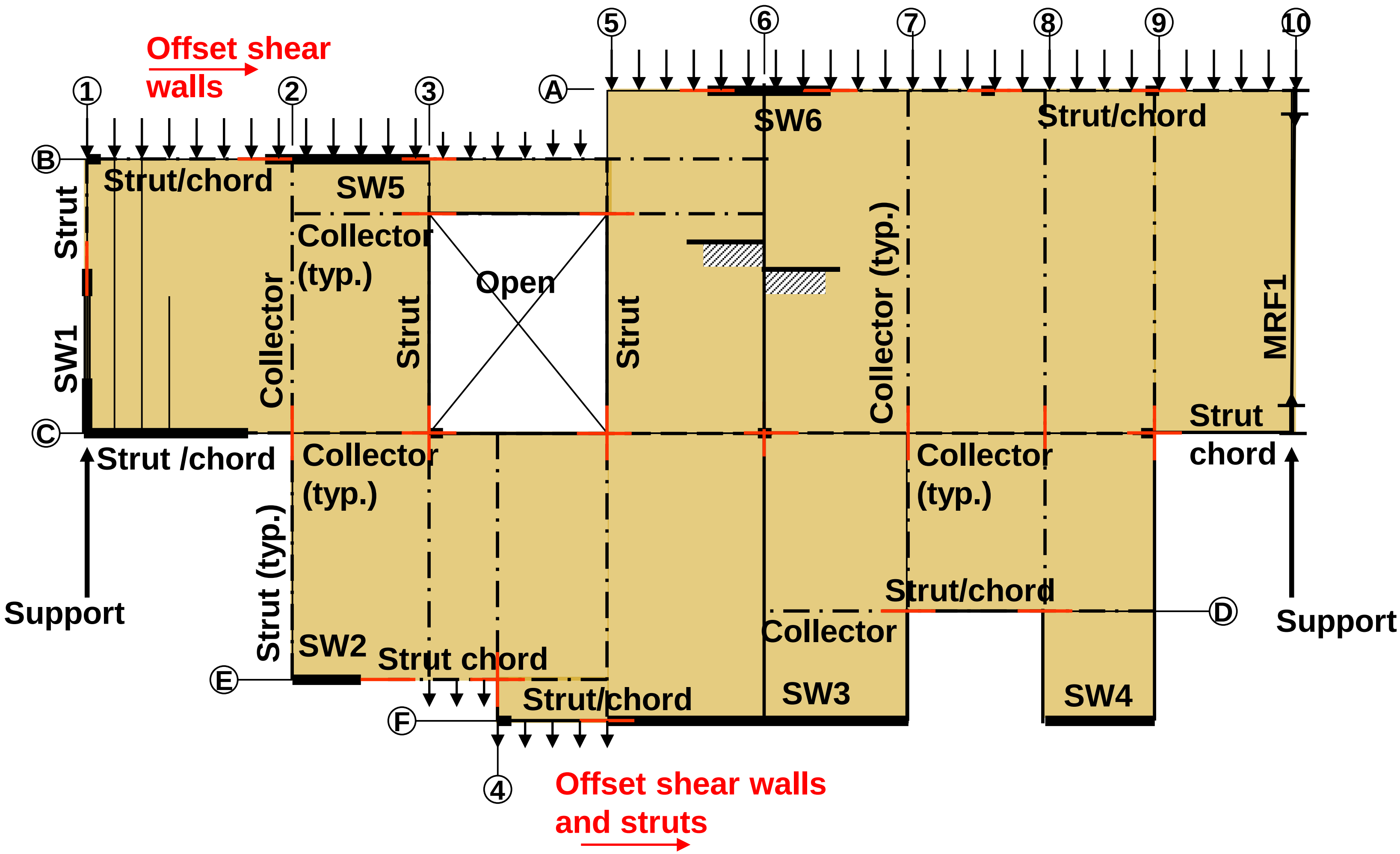
What does this mean?

Complete Continuous Lateral Load Paths



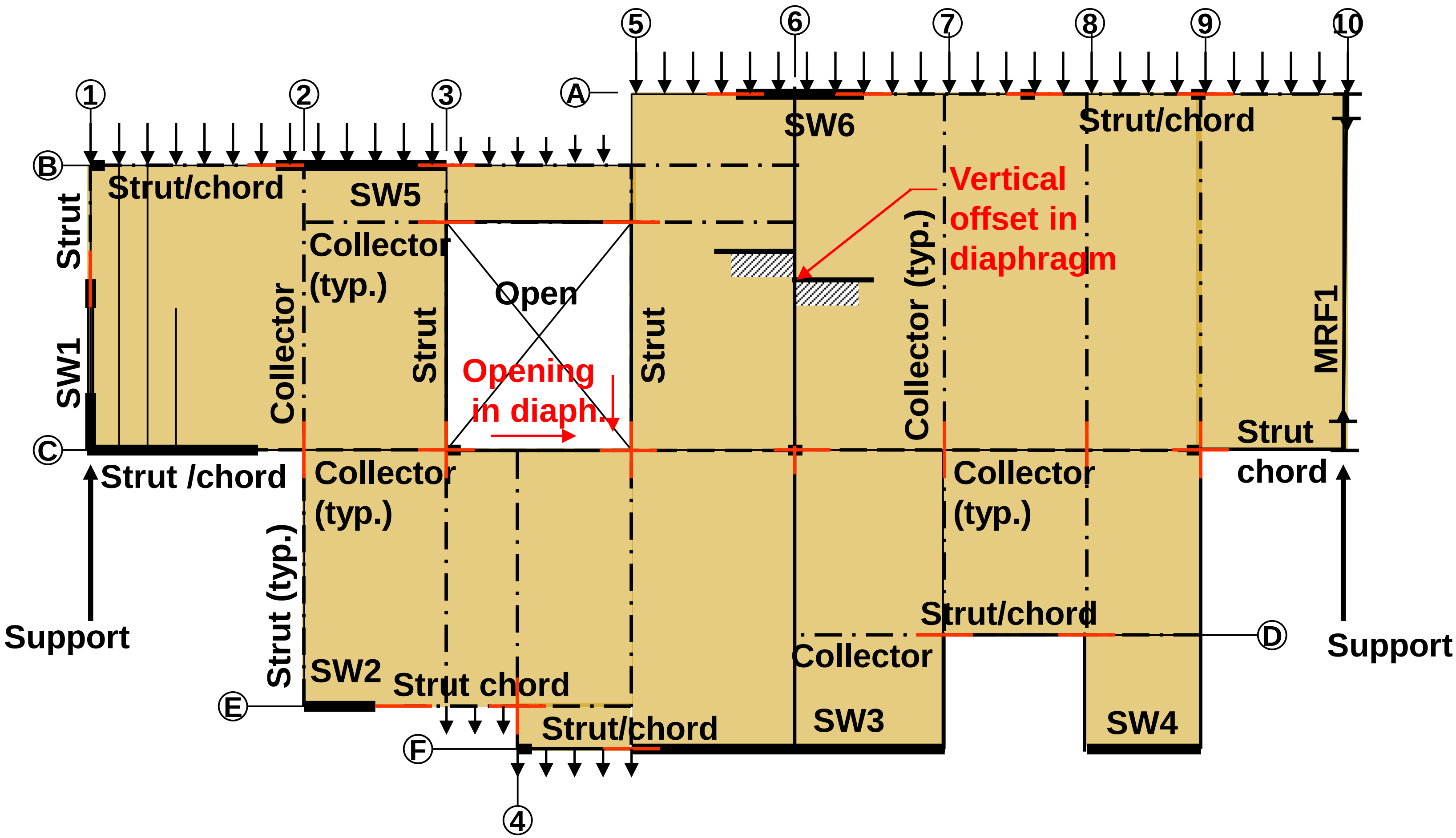
ASCE7-10 Section 1.4-Complete load paths are required including members and their splice connections

Complete Continuous Lateral Load Paths



ASCE7-10 Section **1.4-Complete load paths are required including members and their splice connections**

Complete Continuous Lateral Load Paths



Design:

- IBC 2305.1.1-Openings in shear panels that materially effect their strength shall be fully detailed on the plans and shall have their edges adequately reinforced to transfer all shear stresses.

Complete Continuous Lateral Load Paths

Basic Information

- Boundary Elements
- Complete Load Paths
- **Diaphragm Flexibility**
- Method of Analysis

ASCE7-10 Section 12.3 Diaphragm Flexibility Seismic

Section 12.3.1- The structural analysis shall consider the relative stiffnesses of diaphragms and the vertical elements of the lateral force resisting system.

Start

Is diaphragm untopped steel decking or Wood Structural Panels

Yes →

Is any of the following true?

1 & 2 family Dwelling	Vertical elements one of the following : 1. Steel braced frames 2. Composite steel and concrete braced frames 3. Concrete, masonry, steel SW or composite concrete and steel shear walls.	Light framed construction where all of the following are met: 1. Topping of concrete or similar material is not placed over wood structural panel diaphragms except for non-structural topping not greater than 1 ½" thick. 2. Each line of vertical elements of the seismic force-resisting system complies with the allowable story drift of Table 12.12-1.

Yes → **Idealize as flexible**

No →

No →

Is diaphragm concrete slab or concrete filled steel deck ?

Yes → **Is span to depth ratio ≤ 3 and having no horizontal irregularities ?**

Yes → **Idealize as rigid**

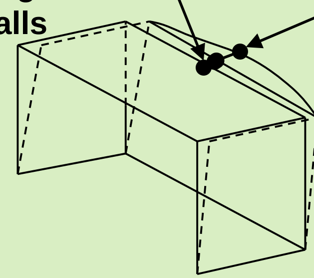
No →

No →

(Could apply to CLT or Heavy timber diaphragms)

Average drift of walls

Maximum diaphragm deflection



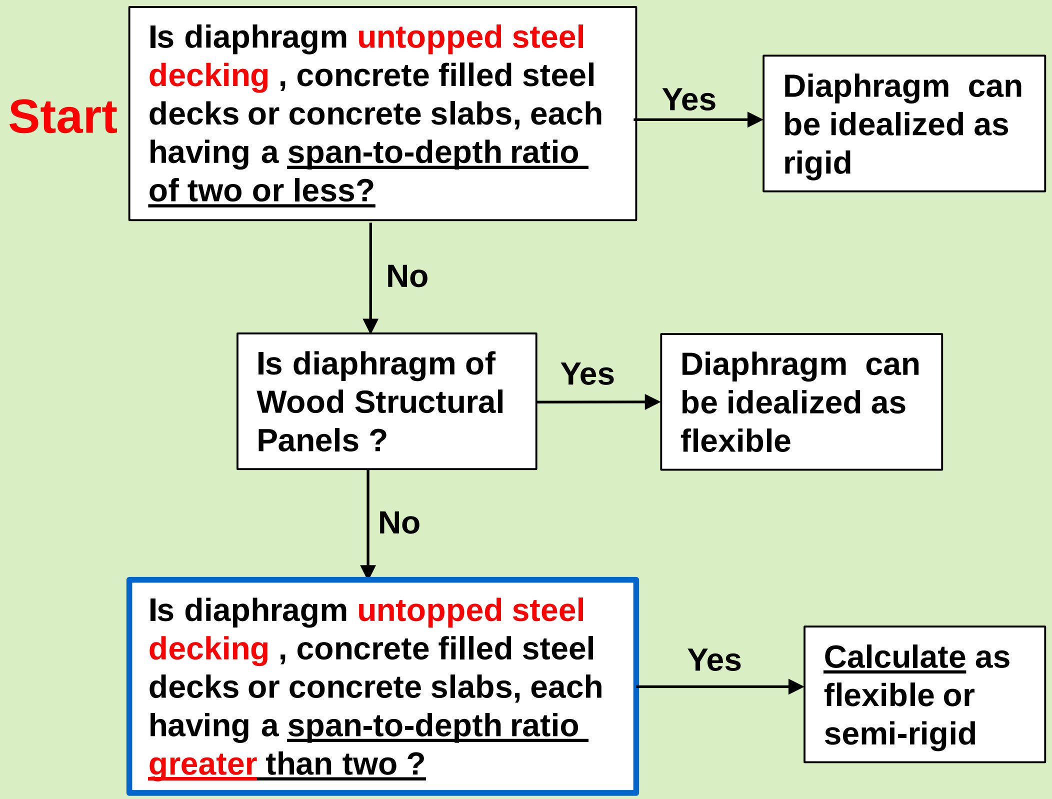
Is maximum diaphragm deflection (MDD) >2x average story drift of vertical elements, using the Equivalent Force Procedure of Section 12.8?

Yes → **Idealize as flexible**

No → **Structural analysis must explicitly include consideration of the stiffness of the diaphragm (i.e. semi-rigid modeling).**

Semi-rigid (Envelope Method)

ASCE7-10, Section 26.2 Diaphragm Flexibility Wind

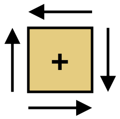


Basic Information

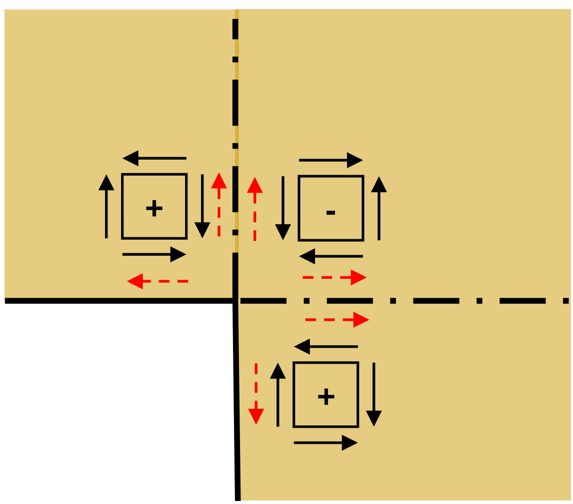
- Boundary Elements
- Complete Load Paths
- Diaphragm stiffness/Flexibility
- **Method of Analysis**

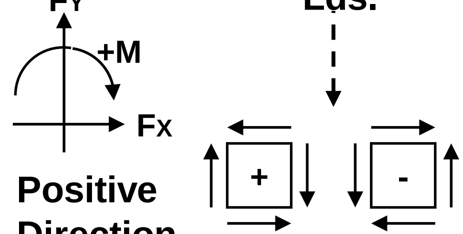
The Visual Shear Transfer Method

How to visually show the distribution of shears through the diagraphragm



Sheathing element symbol for 1 ft x 1 ft square piece of sheathing in static equilibrium (typ.)



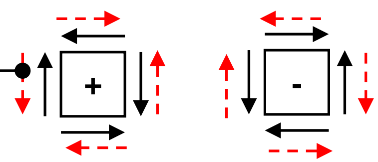


Positive Direction

Transverse Direction (shown)

Shears Applied to Sheathing Elements

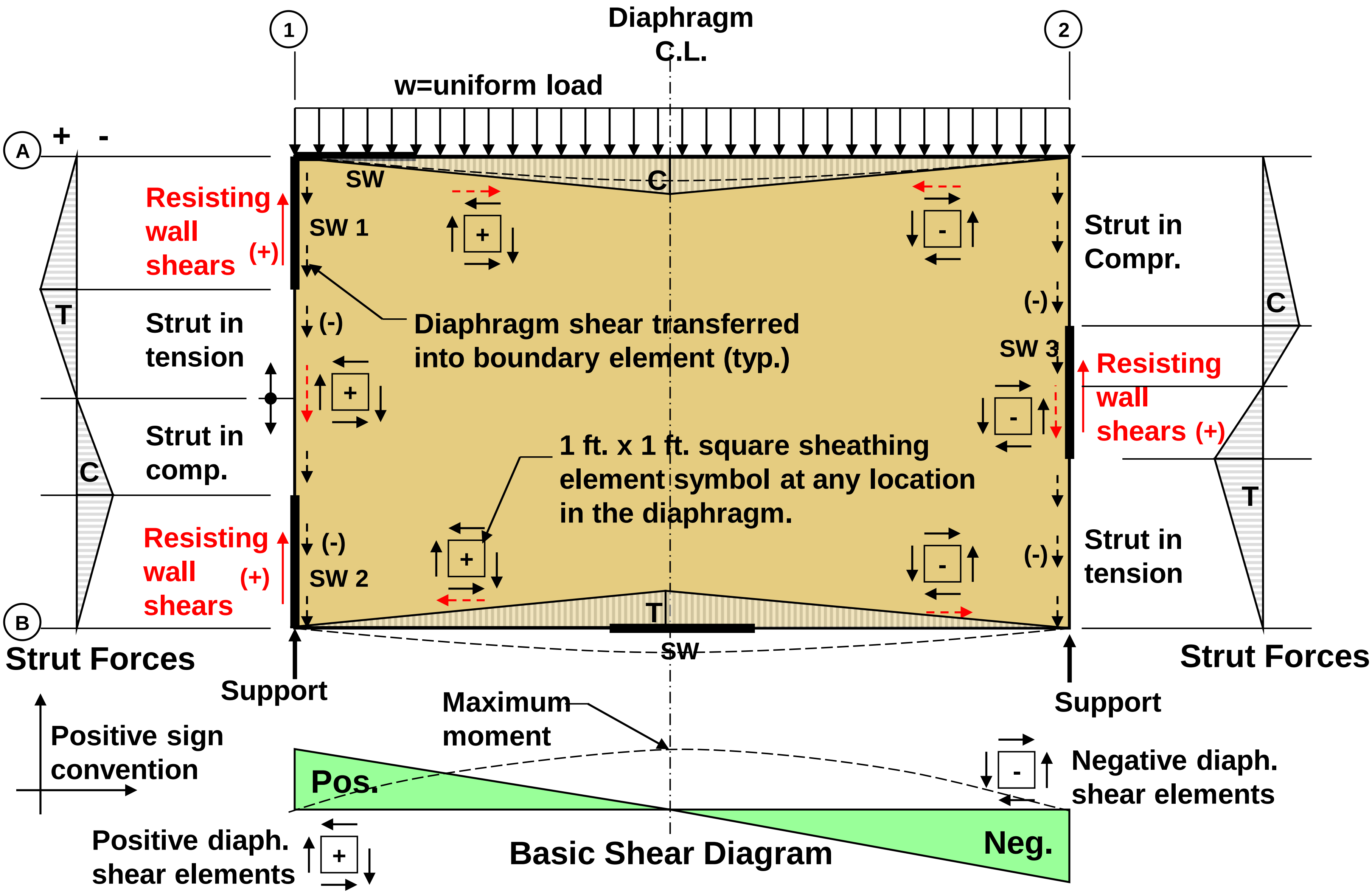
Transfer shears



Unit shear acting on sheathing element (plf)

Unit shear transferred from the sheathing element into the boundary element (plf)

Shears Transferred Into Boundary Elements

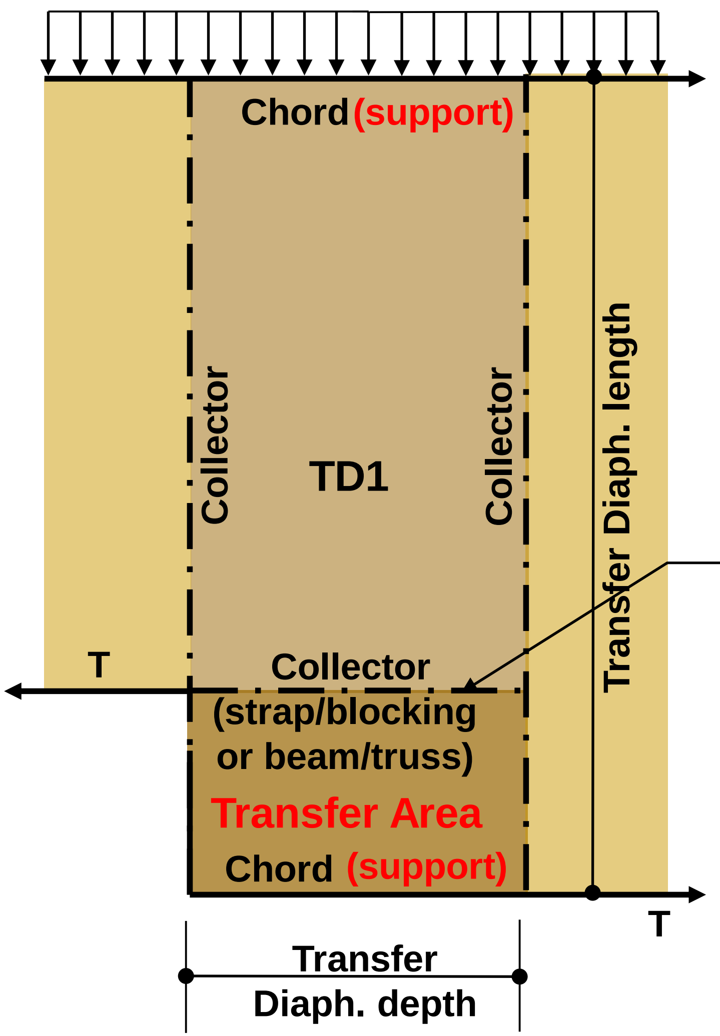


All edges of a diaphragm shall be supported by a boundary element (chord, strut, collector) or other vertical lateral force resisting element (shear wall, frame).

Shear Distribution Into a Simple Diaphragm

The Visual Shear Transfer Method

Introduction to Transfer Diaphragms and Transfer Areas



Transfer Diaphragm

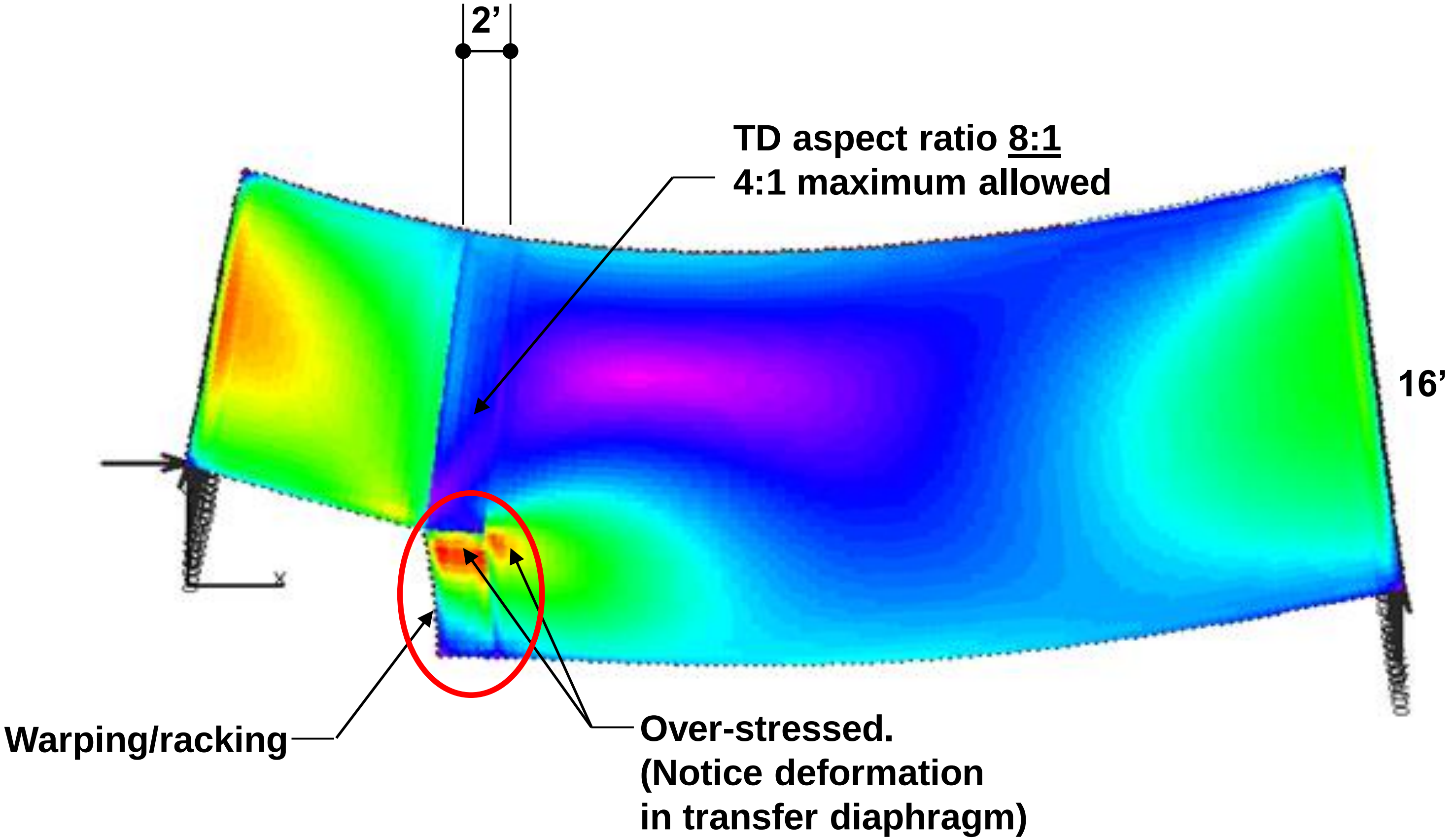
- Sub-diaphragm-don't confuse w/ sub-diaphragms supporting conc./masonry walls
- Transfers local forces out to primary chords/struts of the main diaphragm. (Based on method, ASCE 7 Section 1.4 and SDPWS 4.1.1)
- Maximum TD Aspect Ratio=4:1 (Similar to main diaph.)

Framing members, blocking, and connections shall extend into the diaphragm a sufficient distance to develop the force transferred into the diaphragm. (SDPWS 4.2.1)

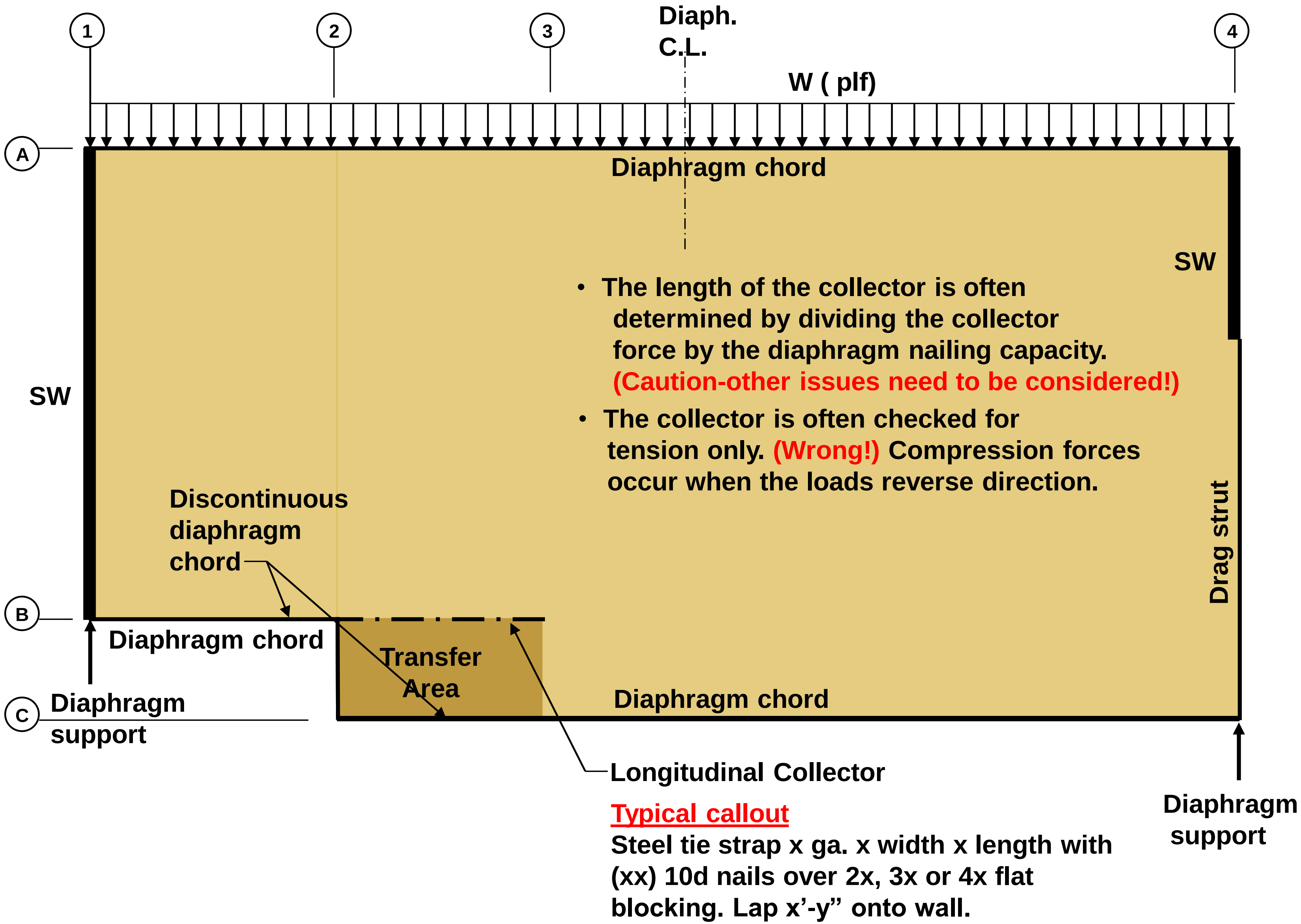
What does this mean?

Collector Length?-My rule of thumb:

- Check length by dividing discontinuous force by the nailing capacity (other issues need to be considered)
- Length=full depth of transfer the diaphragm, set by A/R
- If L<=30' o.k. to use strap/blocking, If > 30' use beam/truss
- Increase TD depth if shears are too high in transfer area

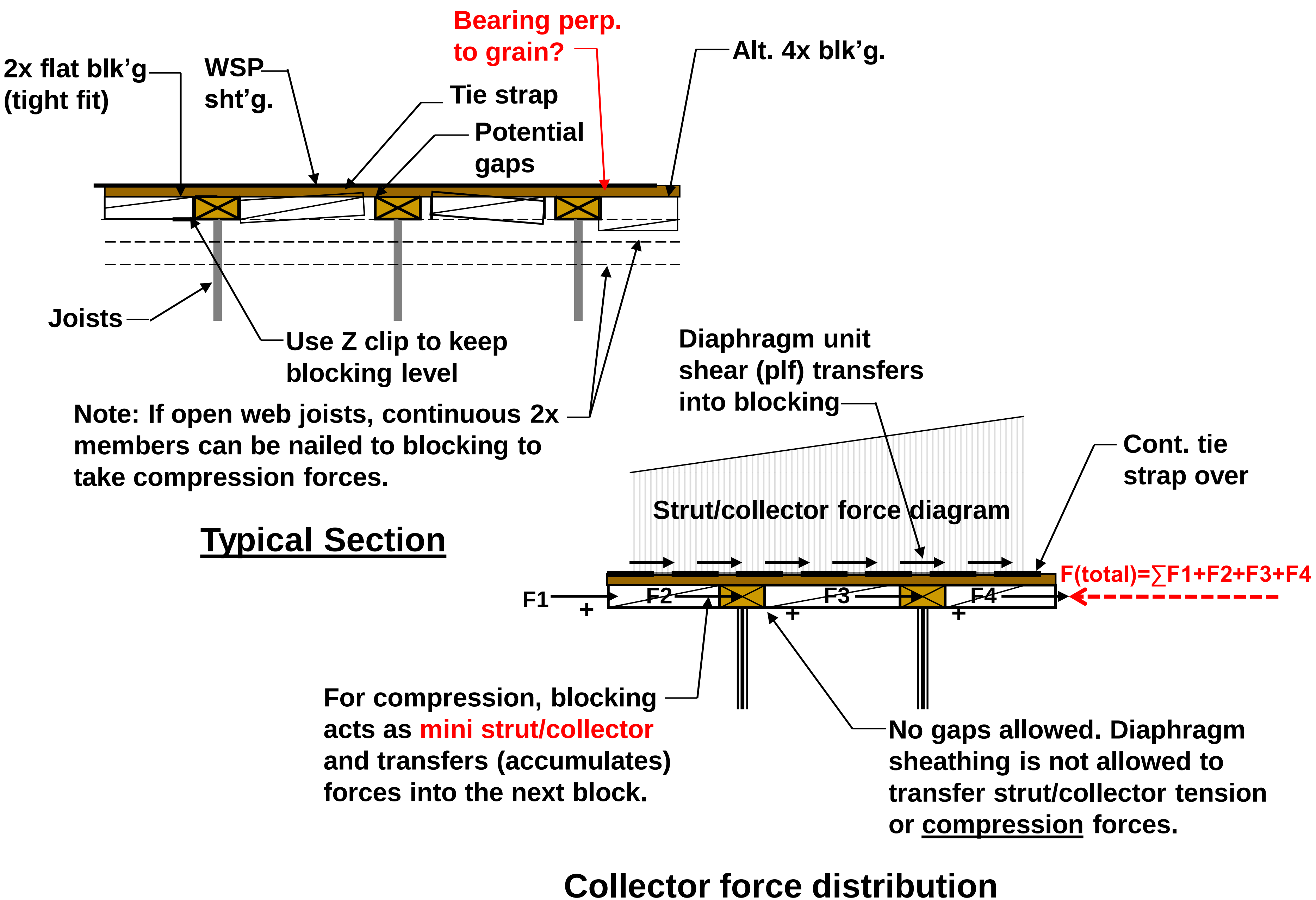


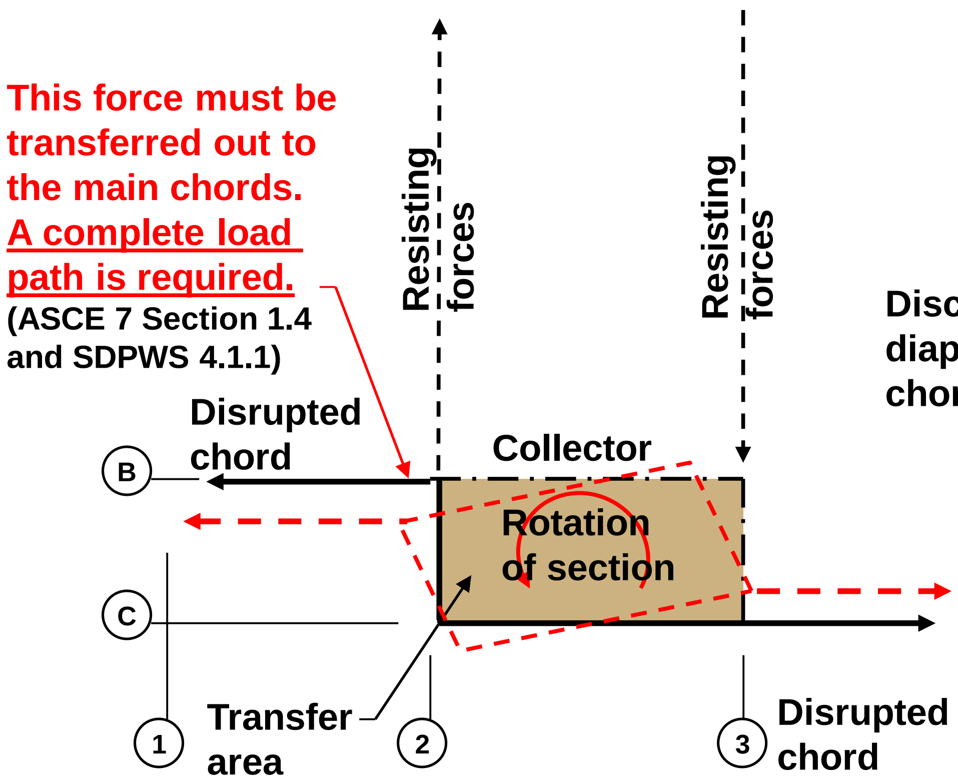
TD Aspect Ratio Too High



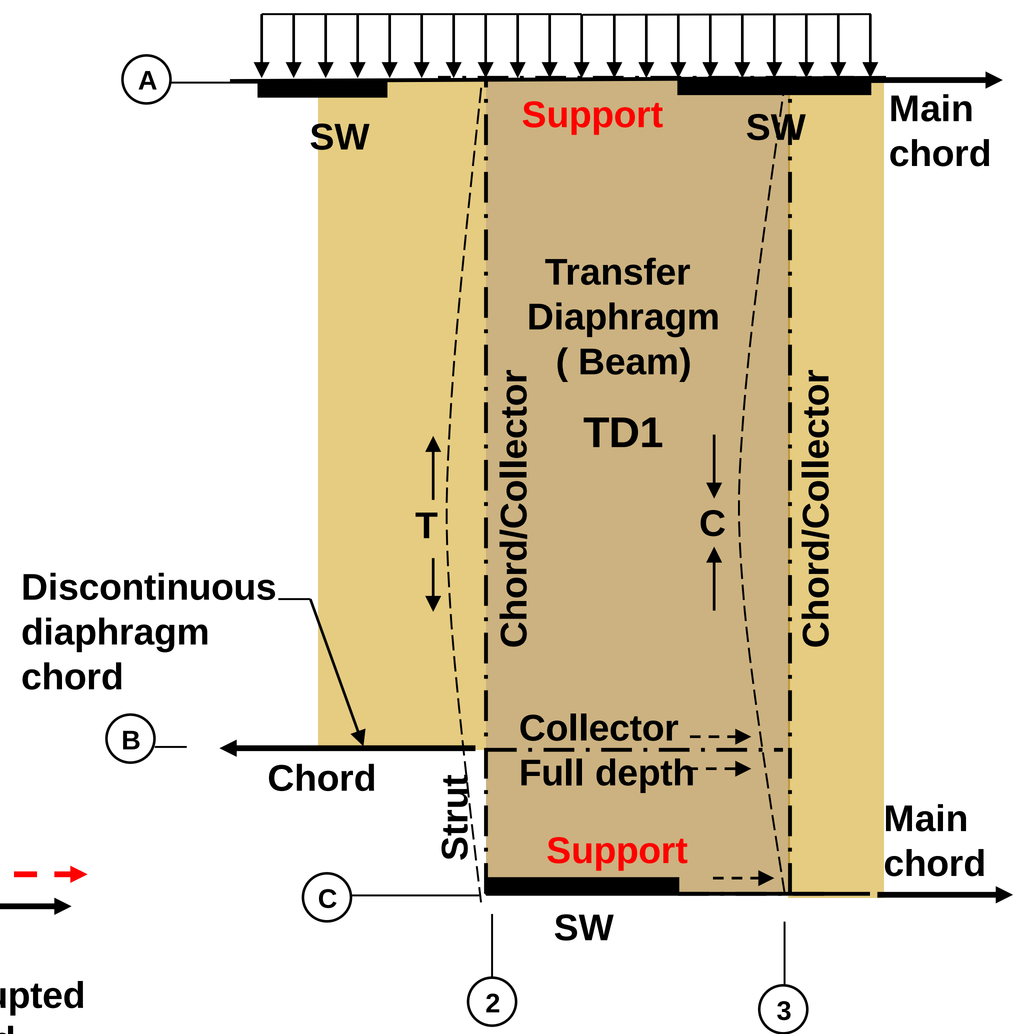
Transfer Diaphragm Members and Elements

Example of Partial Strut/Collector





Transfer area without transverse collectors

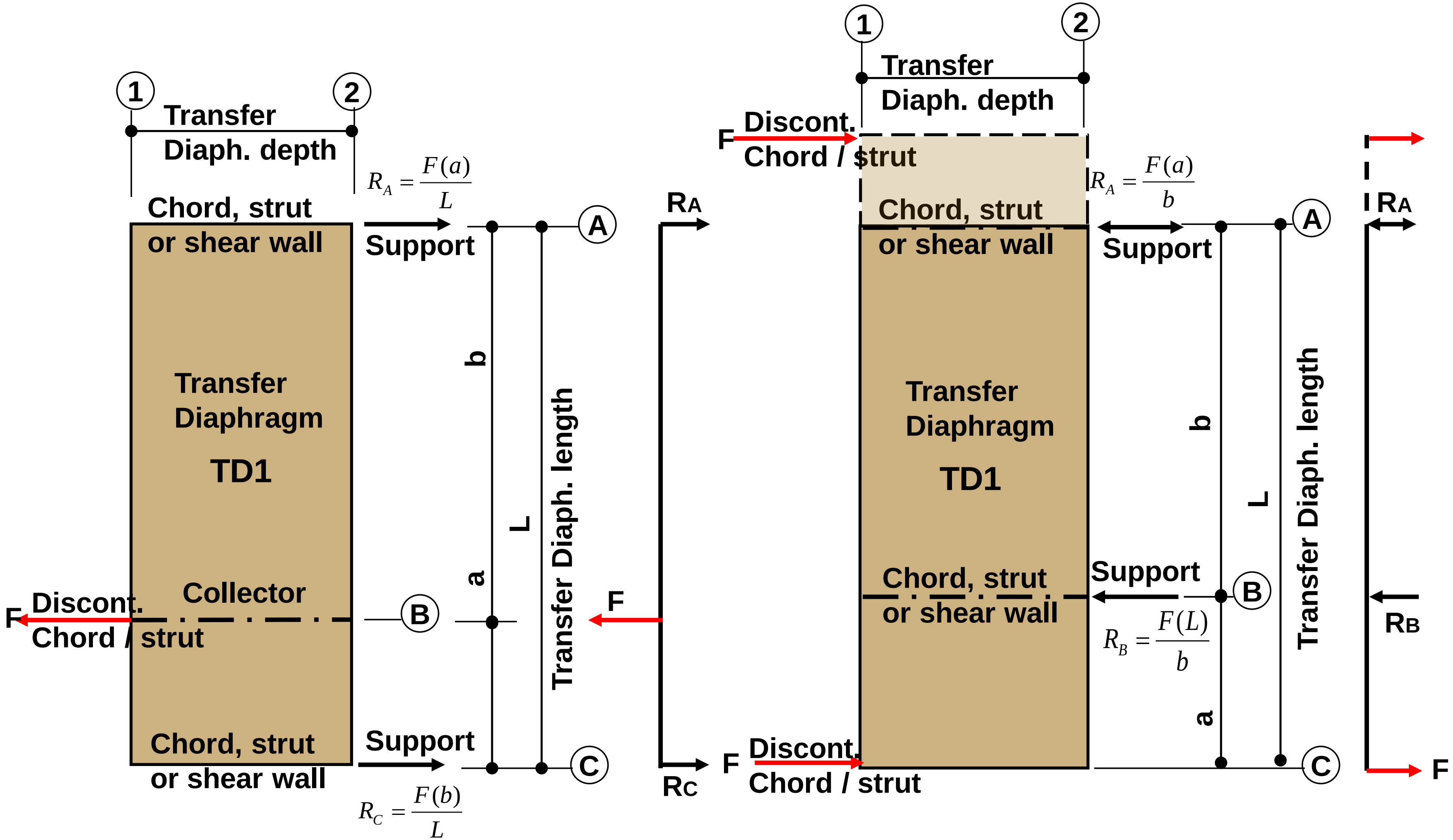


NOTE:

Collector must extend the full depth of the transfer diaphragm

Transfer Mechanism

Transfer using beam concept



Simple Span Transfer Diaphragm

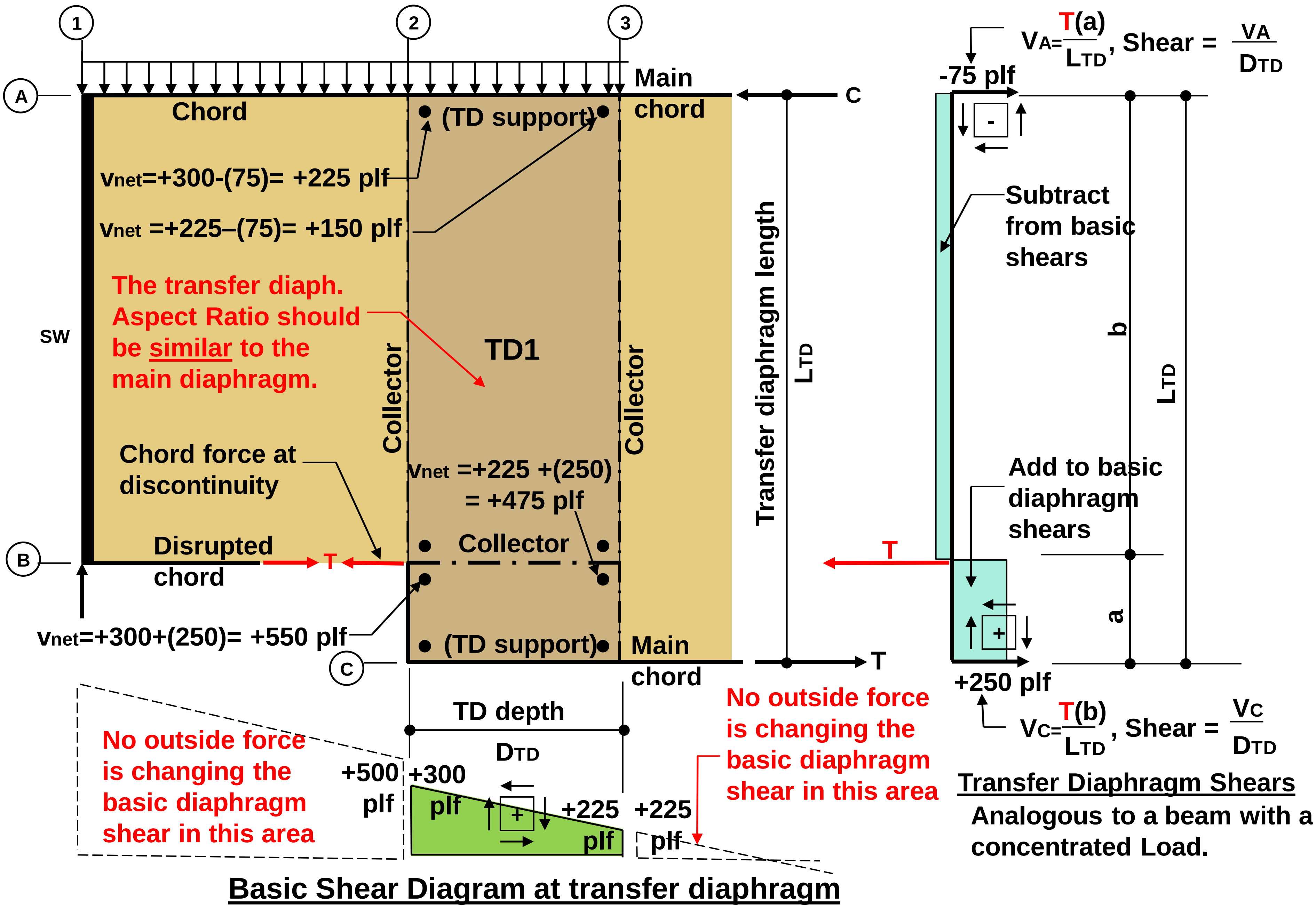
Analogous to a simple span beam with a concentrated load

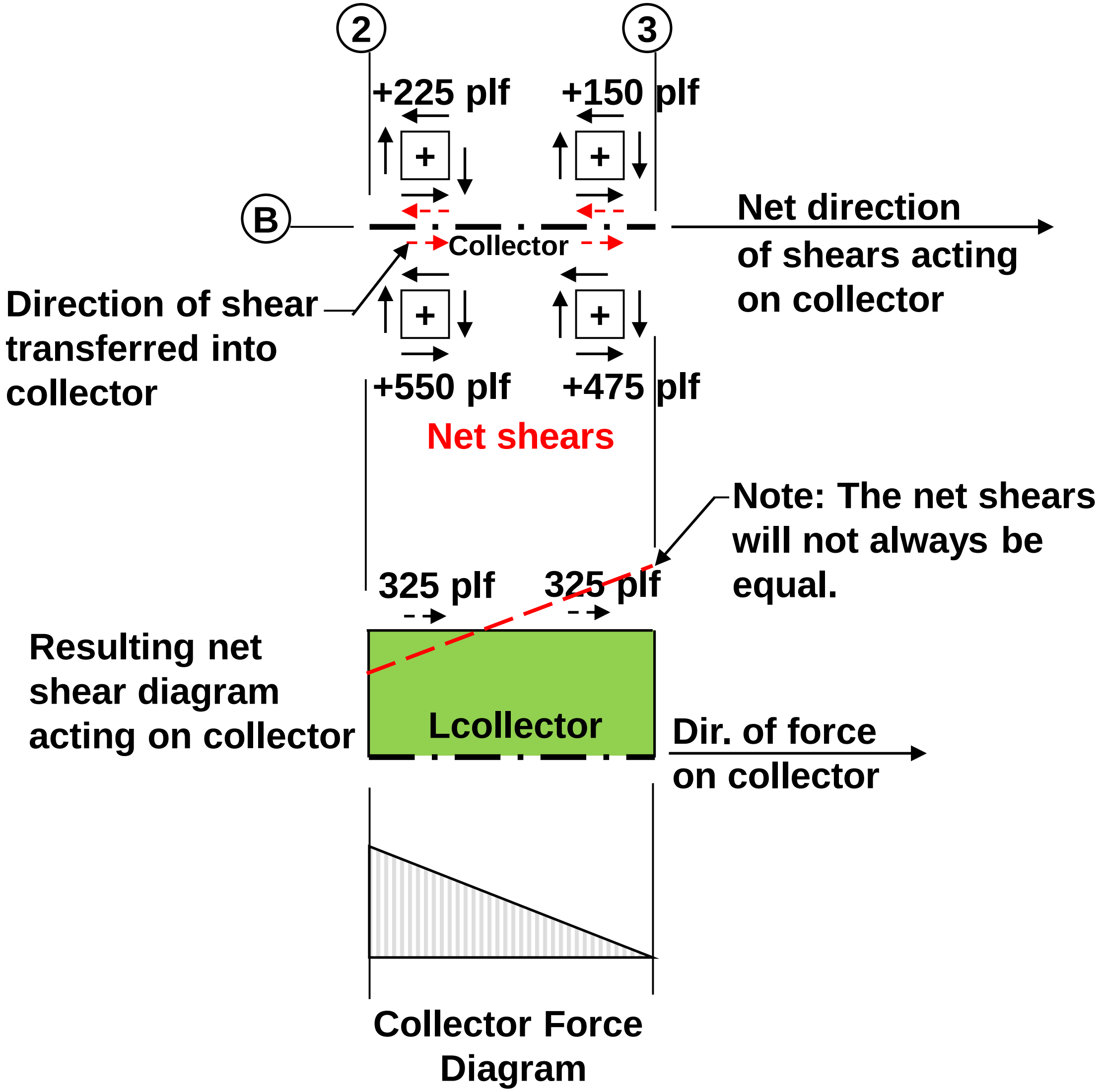
Propped Cantilever Transfer Diaphragm

Analogous to a propped cantilever beam with a concentrated load

Simple Span and Propped Cantilever Transfer Diaphragms

Method of Analysis-Method by Edward F. Diekmann





- Place the net diaphragm shear on each side of the collector
- Place the transfer shears on each side of the collector
- Sum shears on collector (based upon direction of shears transferred onto collector).

Shear left=+550-225= +325 plf

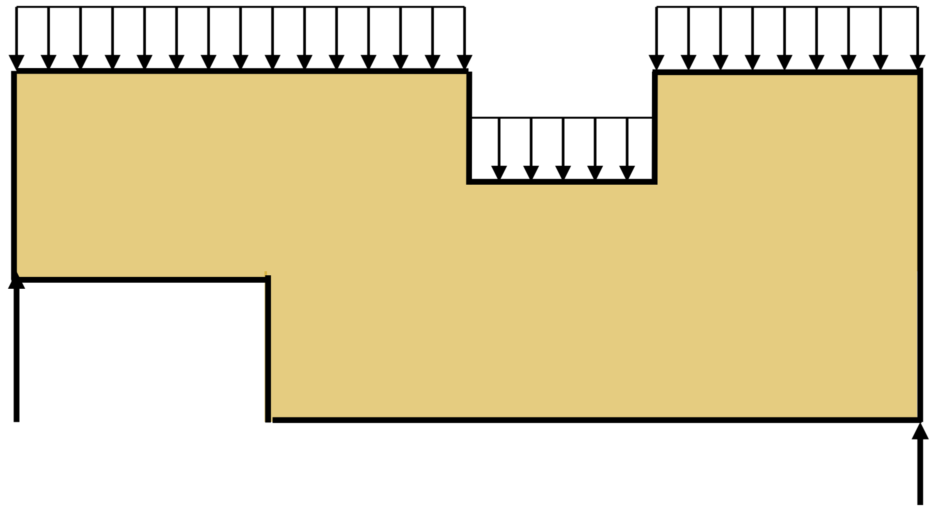
Shear right=+475-150=+325 plf

- Collector force=area of shear diagram

$$F_{collector}=\frac{(325+325)(L_{collector})}{2}$$

Shear Distribution Into The Collector

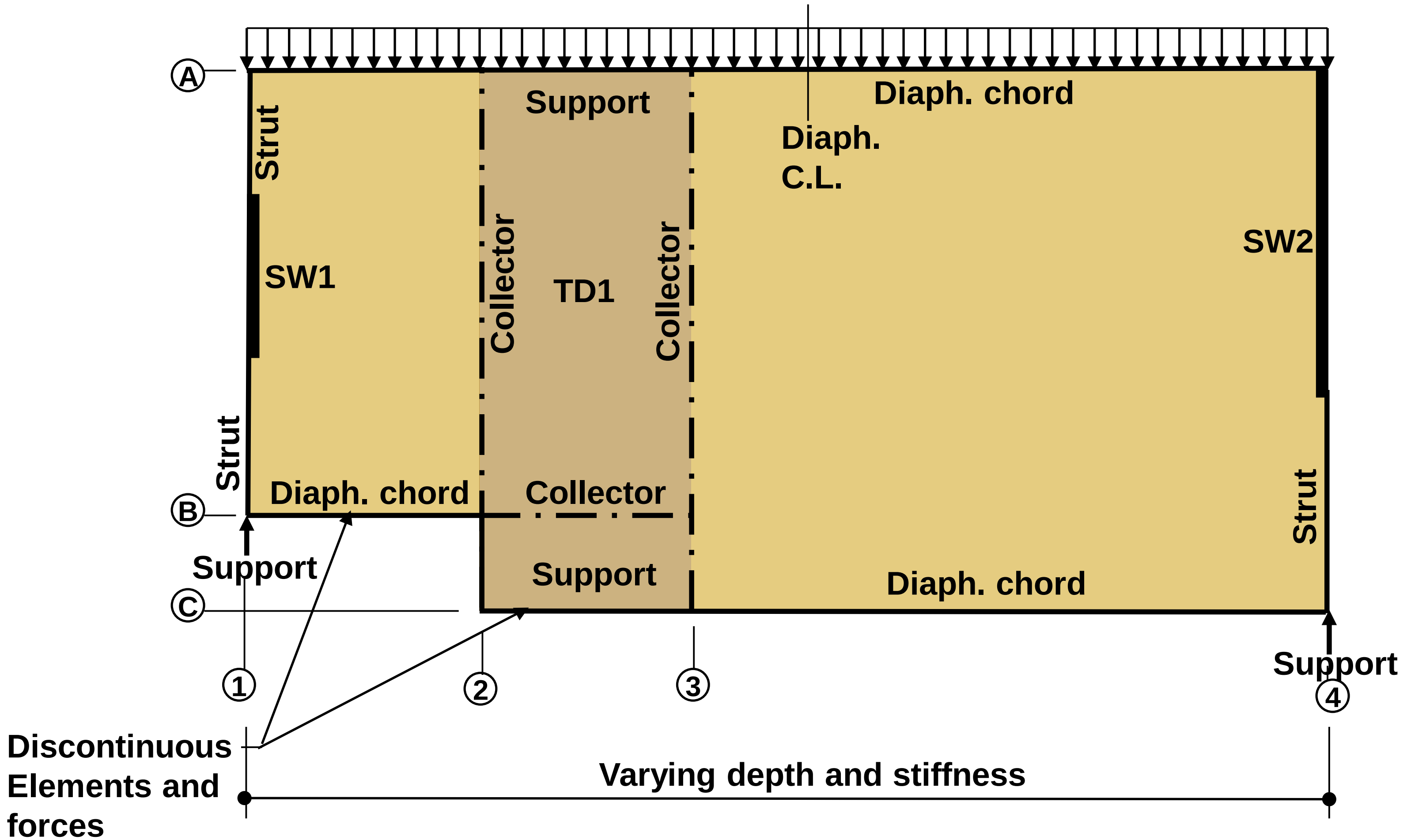
Diaphragms with Horizontal Offsets



Irregularity Requirements for Diaphragms with Horizontal End Offsets-Seismic

A Type 2 Horizontal Irregularity (Re-entrant corner) exists where both projections > 15% of plan dimension in given direction. SDC D-F

- **Triggers Section 12.3.3.4**
- **Can also trigger a Type 3 Horizontal Irregularity- abrupt discontinuity or variation in stiffness in diaphragm SDC D-F**

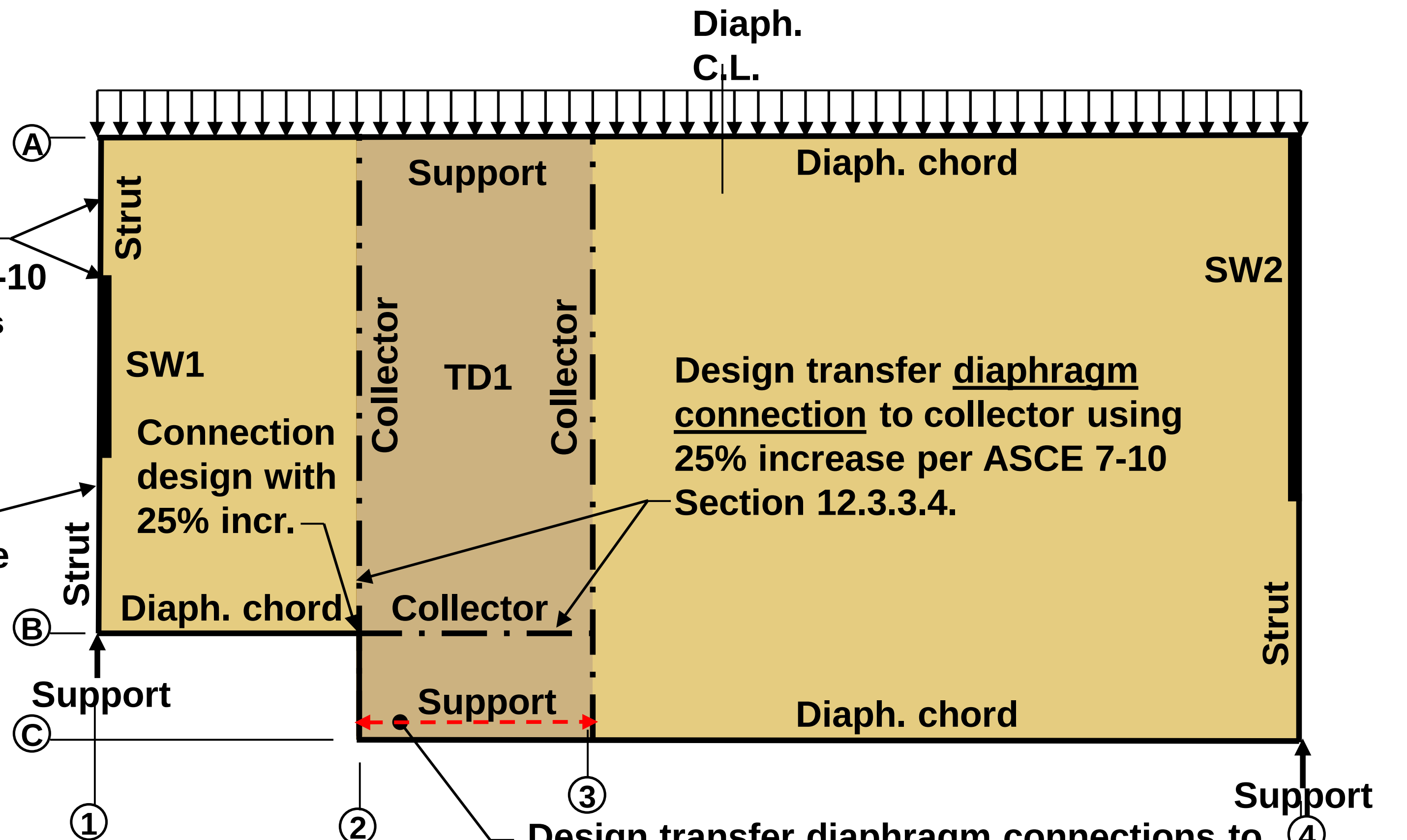


Irregularity Requirements for Diaphragms with Horizontal End Offsets-Seismic

ASCE 7-10 Section 12.3.3.4 –A 25% increase is required in diaphragm (inertial) design forces (Fpx) for Type 2 or Type 3 horizontal irregularities located in (SDC D-F) for the following elements:

- Connections of diaphragm to vertical elements and collectors (diaphragm supporting elements-TD)
- Collectors and their connections to vertical elements

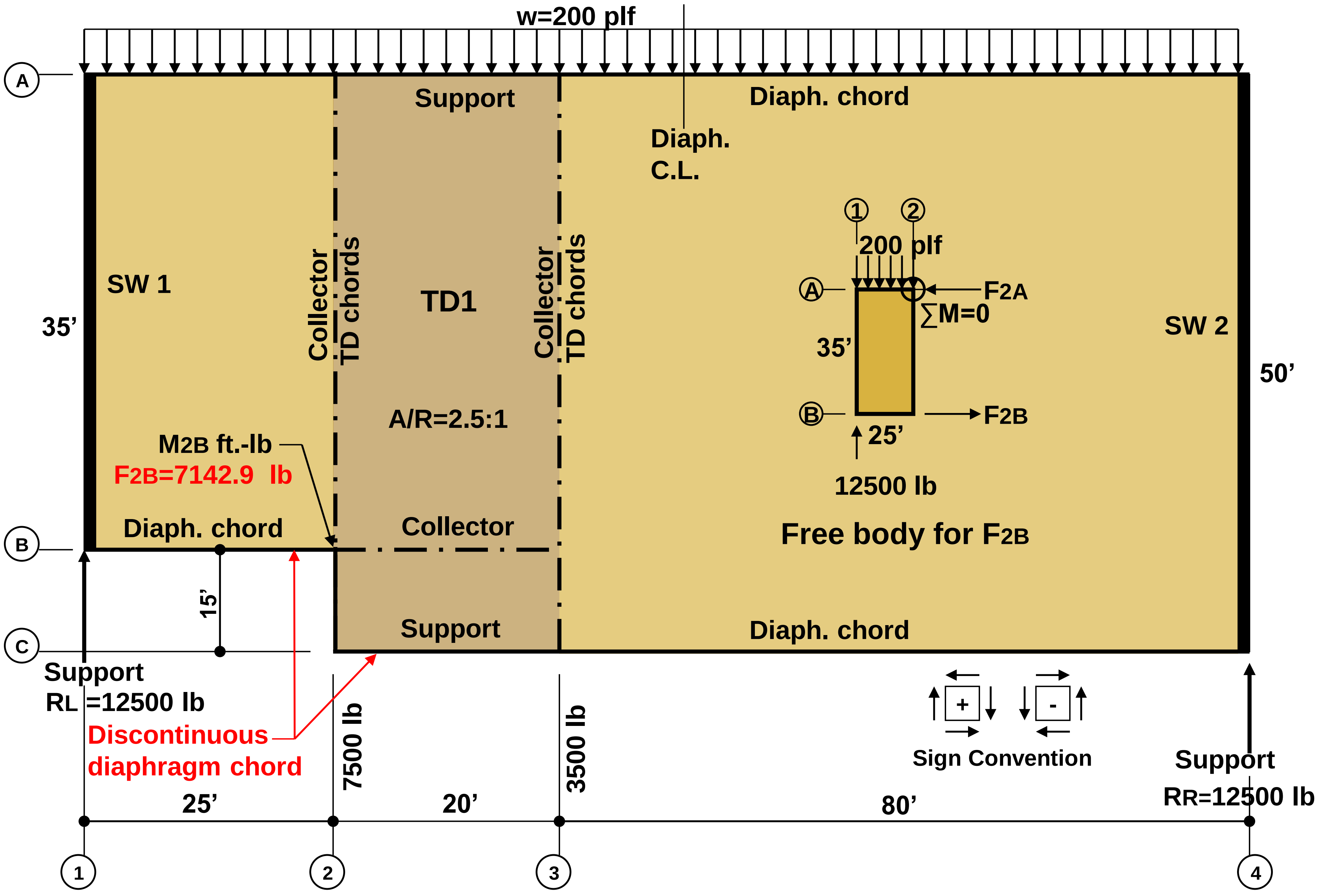
Exception: Forces using the seismic load effects including the over-strength factor of Section 12.4.3 need not be increased.



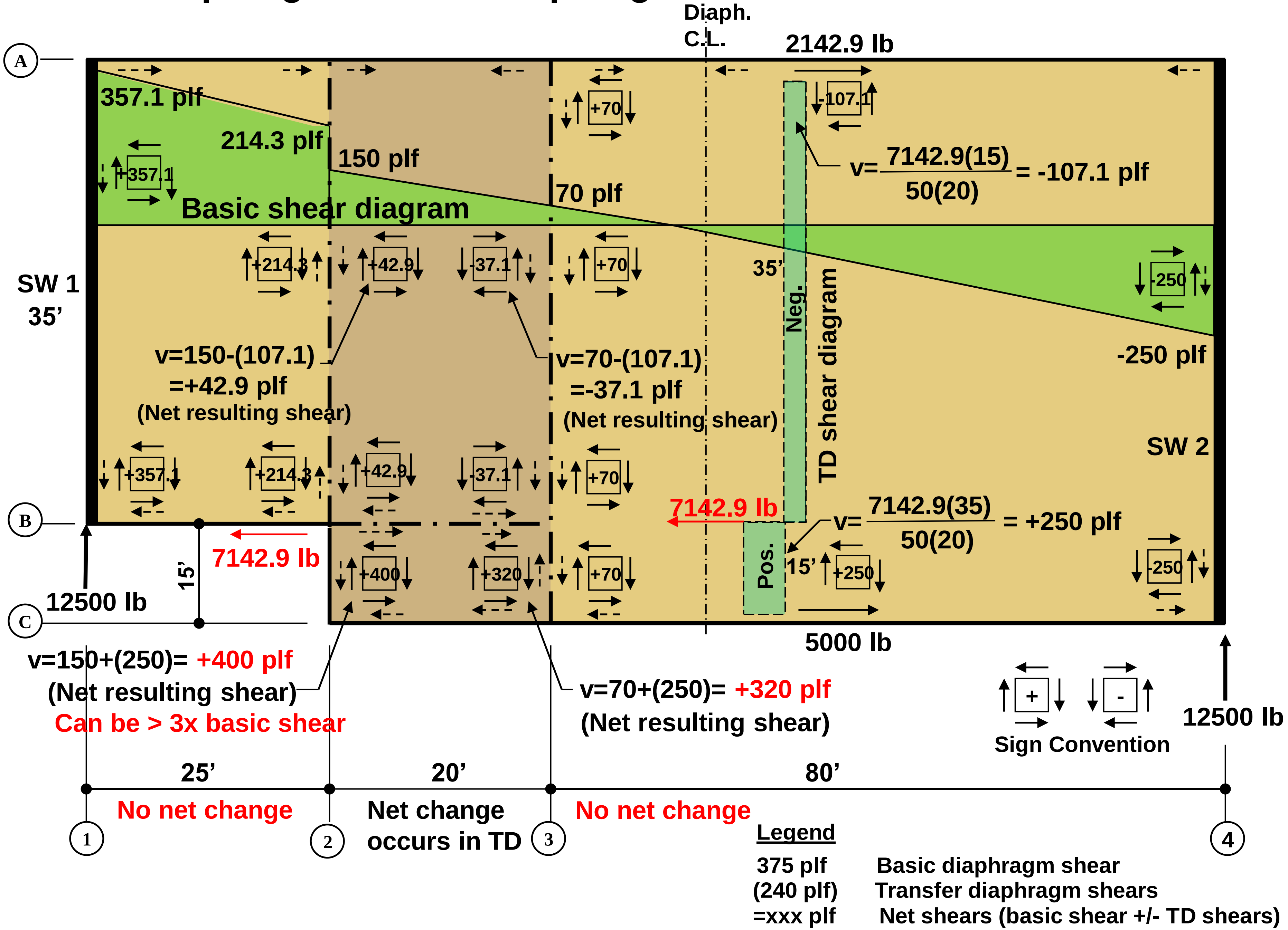
- Diaphragm shears are not required to be increased 25%.

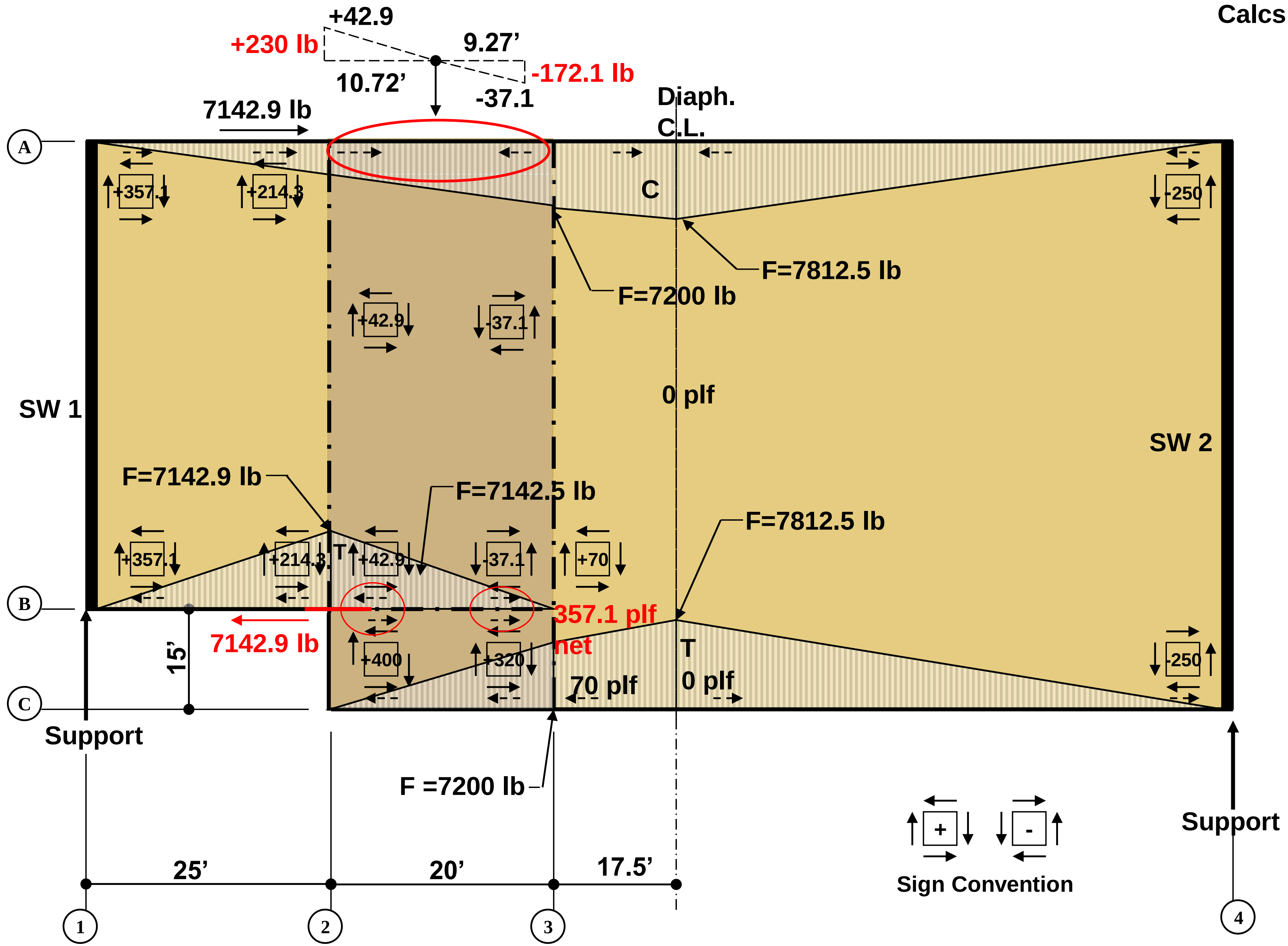
See 12.10.2 & 12.10.2.1 for collectors

Example 1-Diaphragm with Horizontal End Offset-Transverse Loading

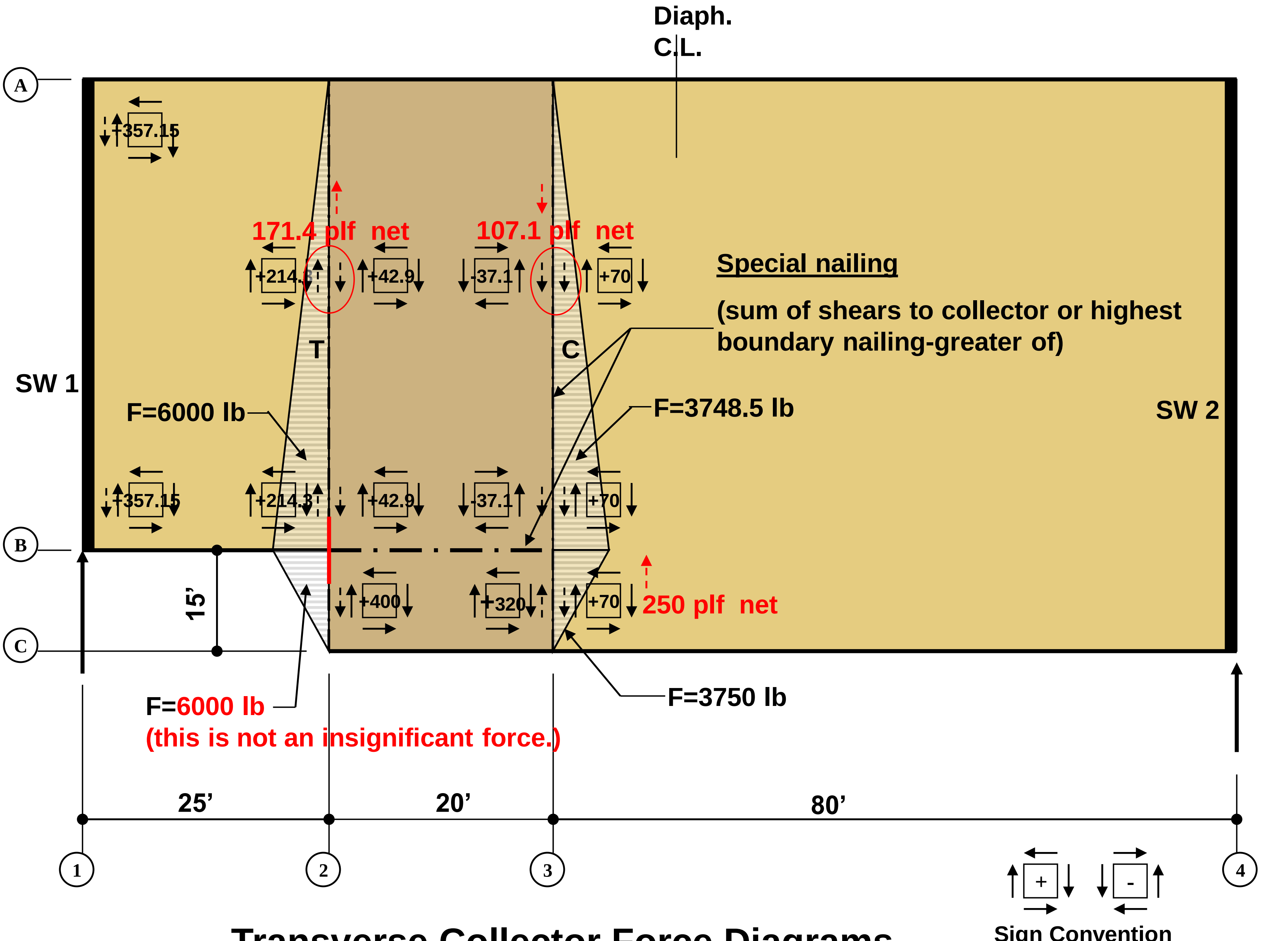


Transfer Diaphragm and Net Diaphragm Shear

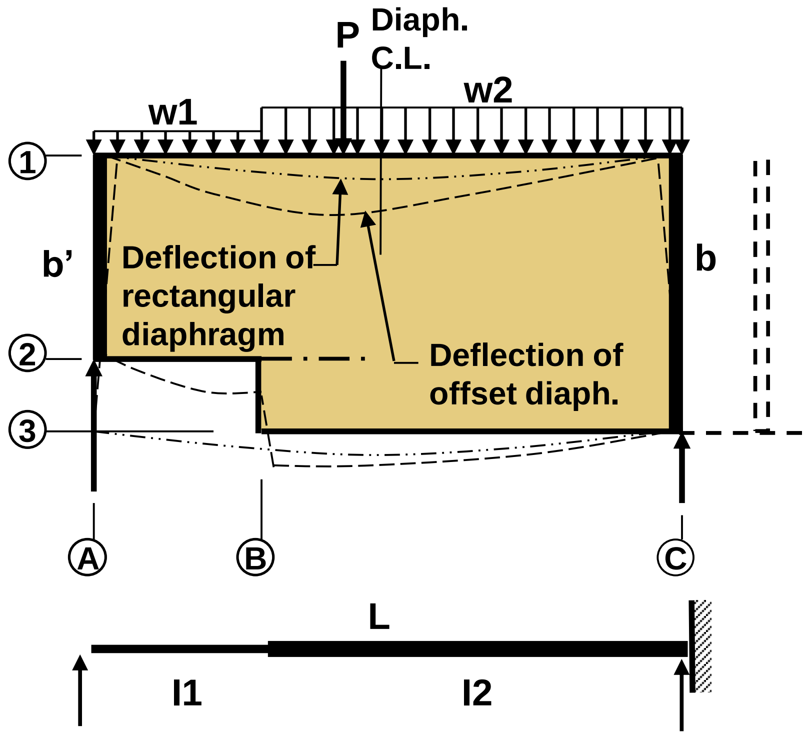




Longitudinal Chord Force Diagrams



Transverse Collector Force Diagrams



Diaphragm Deflection Equations

Equation variables for offset diaphragms

- Varying uniform loads
- Concentrated loads from discontinuous shear walls
- Varying moments of inertia, and sometimes
- Different support conditions

ATC7

- Modify the bending and shear portion of the standard rectangular deflection equation to fit the model:

$$\Delta_{TL} = \Delta_B + \Delta_S + 0.188Le_n + \frac{\Sigma(\Delta_C X)}{2b}$$

where

$$\Delta_B = \int_a^b \frac{mM}{EI_1}dx + \int_b^c \frac{mM}{EI_2}dx, \text{ and}$$

$$\Delta_S = \frac{bt}{2GA^2}\left[\int_a^b \frac{wx}{\left(\frac{b'}{b}\right)^2}dx + \int_b^c wx\,dx\right] = \int_0^L \frac{vV}{Gt}dx$$

SDPWS combines

$$\Delta_{TL} = \frac{5vL^3}{8EAb} + \frac{vL}{4G_t} + 0.188Le_n + \frac{\Sigma(\Delta_C X)}{2b}$$

Cannot use

IBC Eq. 23 – 1 APA equation

Bending deflection

Shear deflection

Nail slip Adjusted for non-uniform nailing (ATC-7/APA)

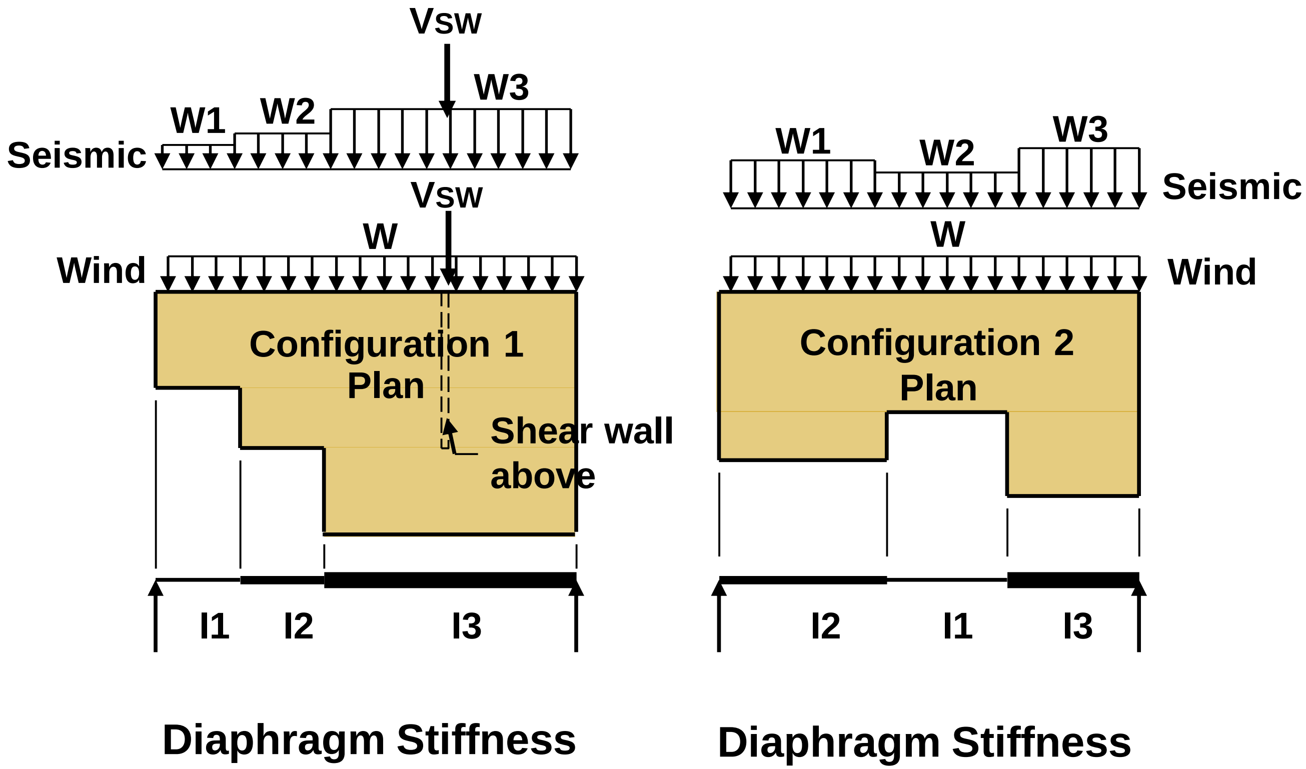
Chord slip

Shear Deflection -USDA Research Note FPL-0210

- Simplification of the conventional energy method.
- The integrations of the equations can be reduced to multiplying the total area of the shear diagram due to the general loading by the ordinate of the shear diagram due to a dummy load applied at the desired point of shear deflection.

Standard deflection equation for simple span, rectangular, rigid supports, fully blocked, uniformly loaded, constant cross section (Δ at C.L.)

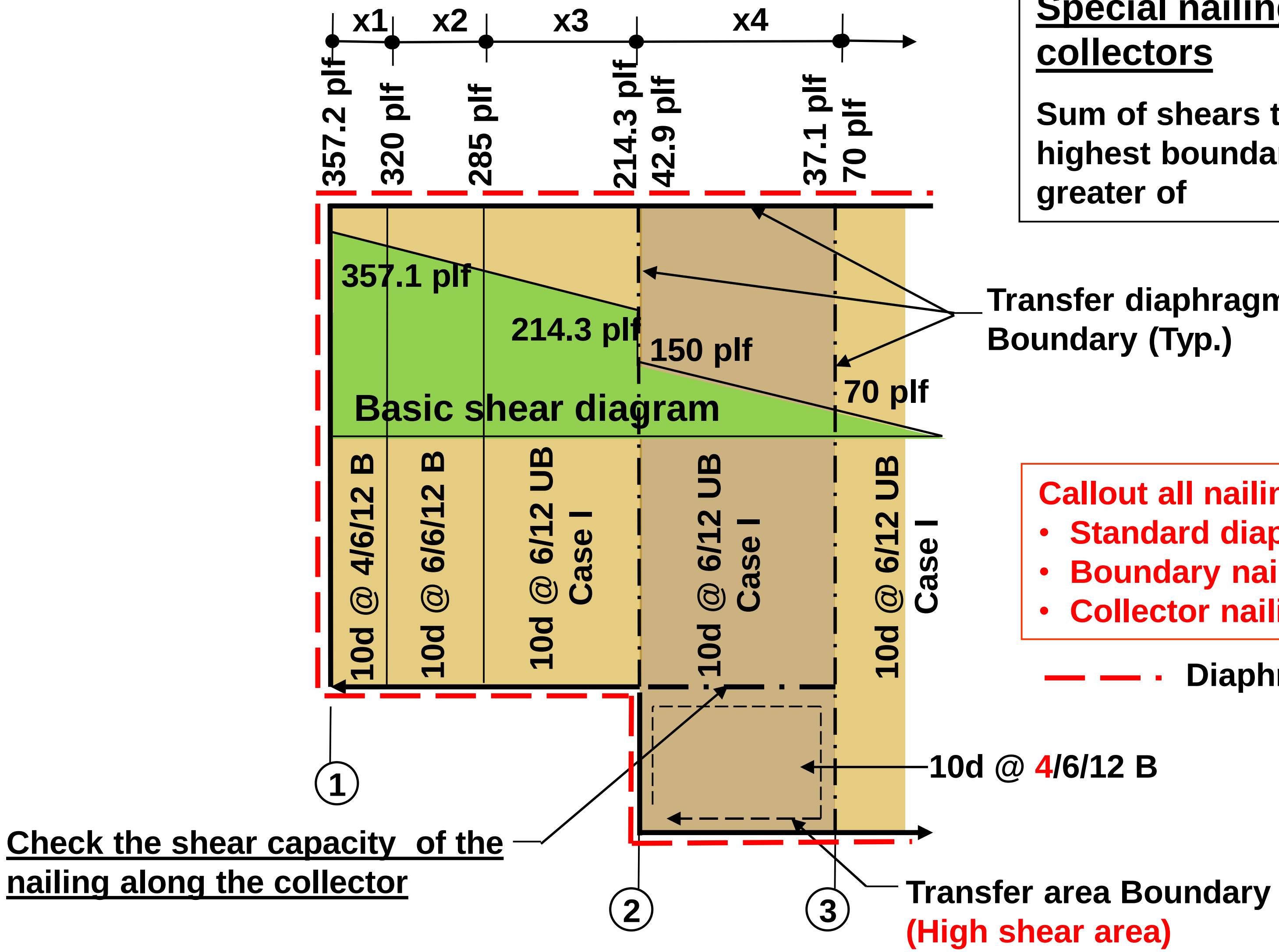
NOTE: Multiply deflection x 2.5 for unblocked diaphragm
Multiply nail slip by 1.2 if not Structural I plywood



Diaphragm Bending Deflection Modeling- Other Layouts

Special nailing along collectors

Sum of shears to collector or highest boundary nailing-greater of



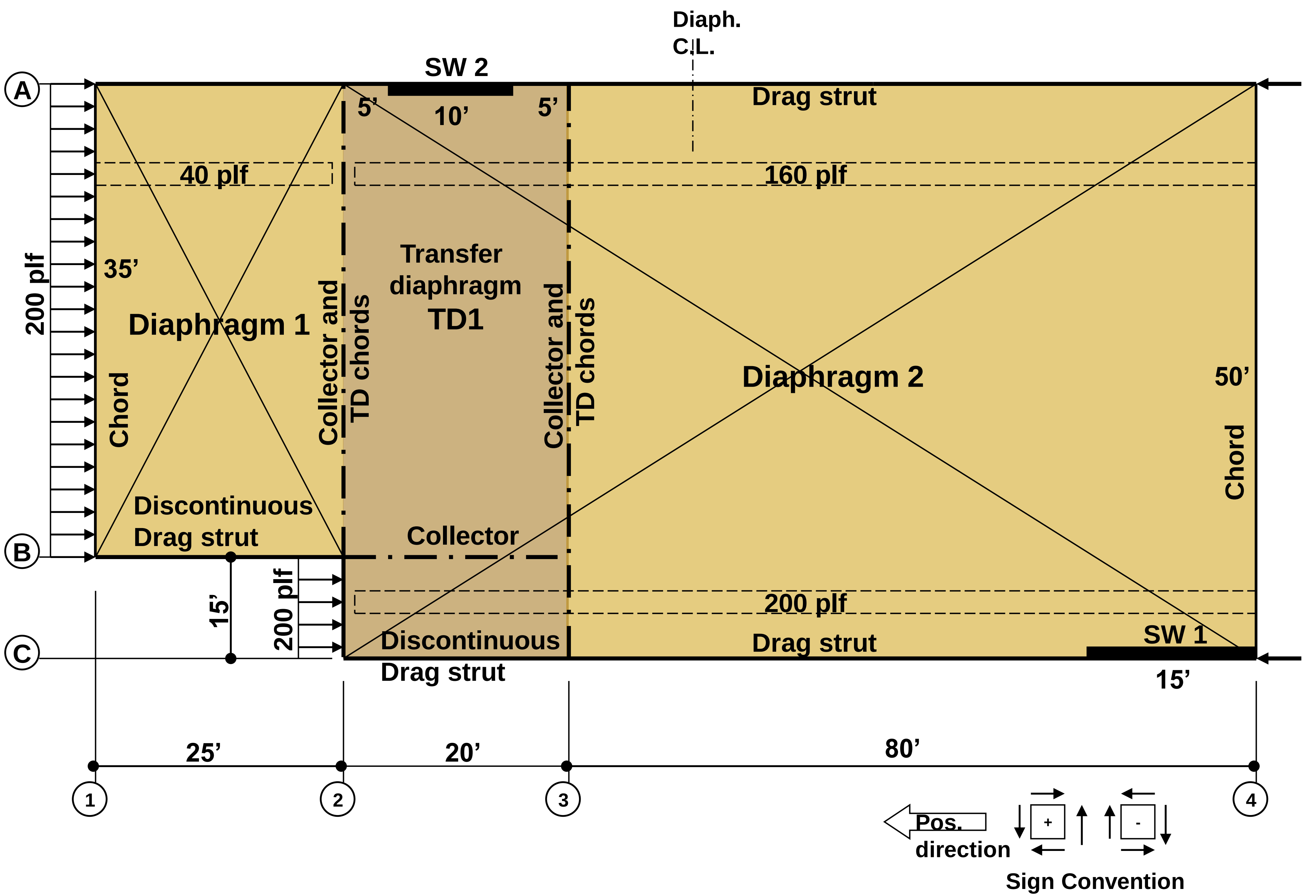
Callout all nailing on drawings:

- Standard diaphragm nailing
- Boundary nailing
- Collector nailing

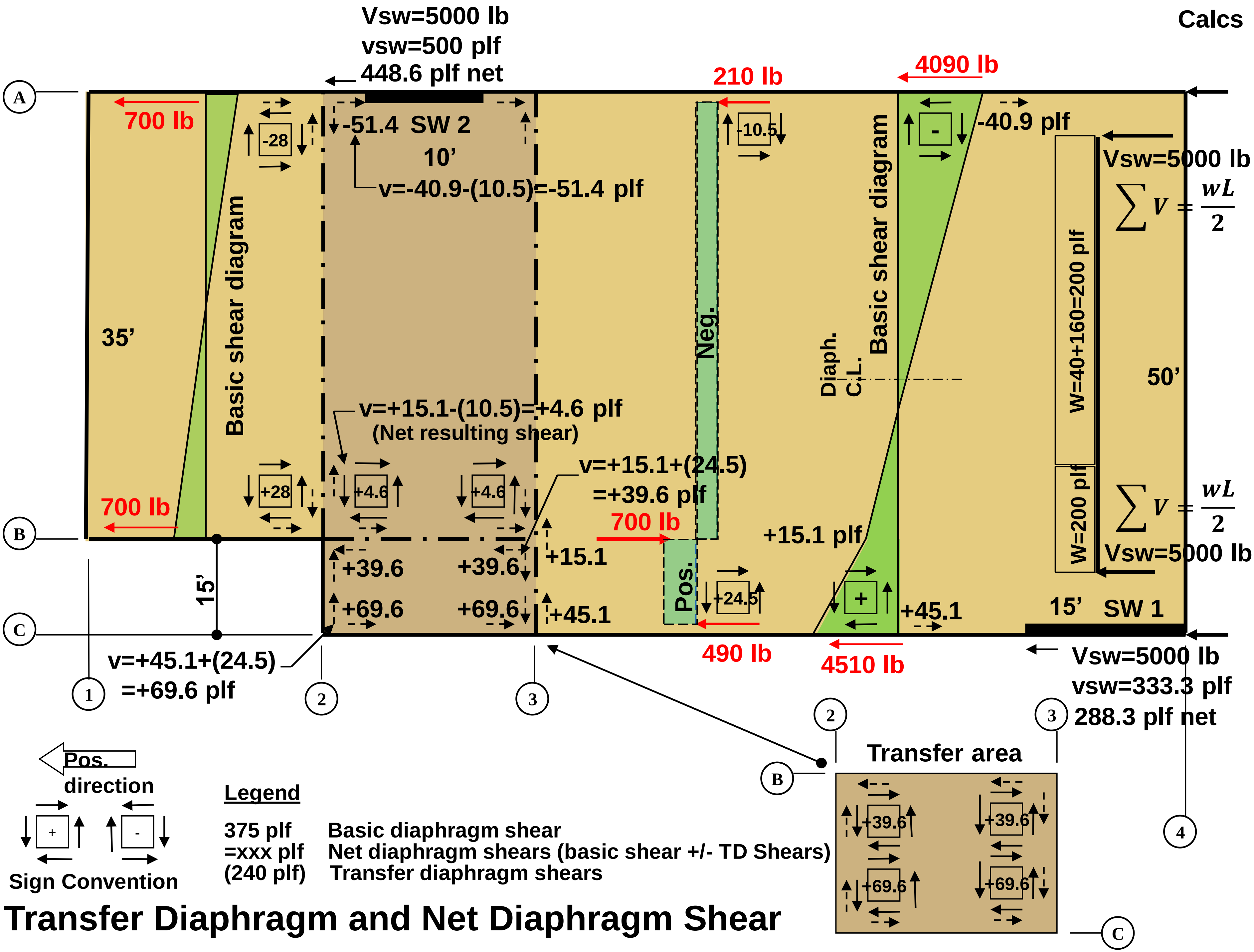
Boundary locations

Diaphragm Nailing Callouts

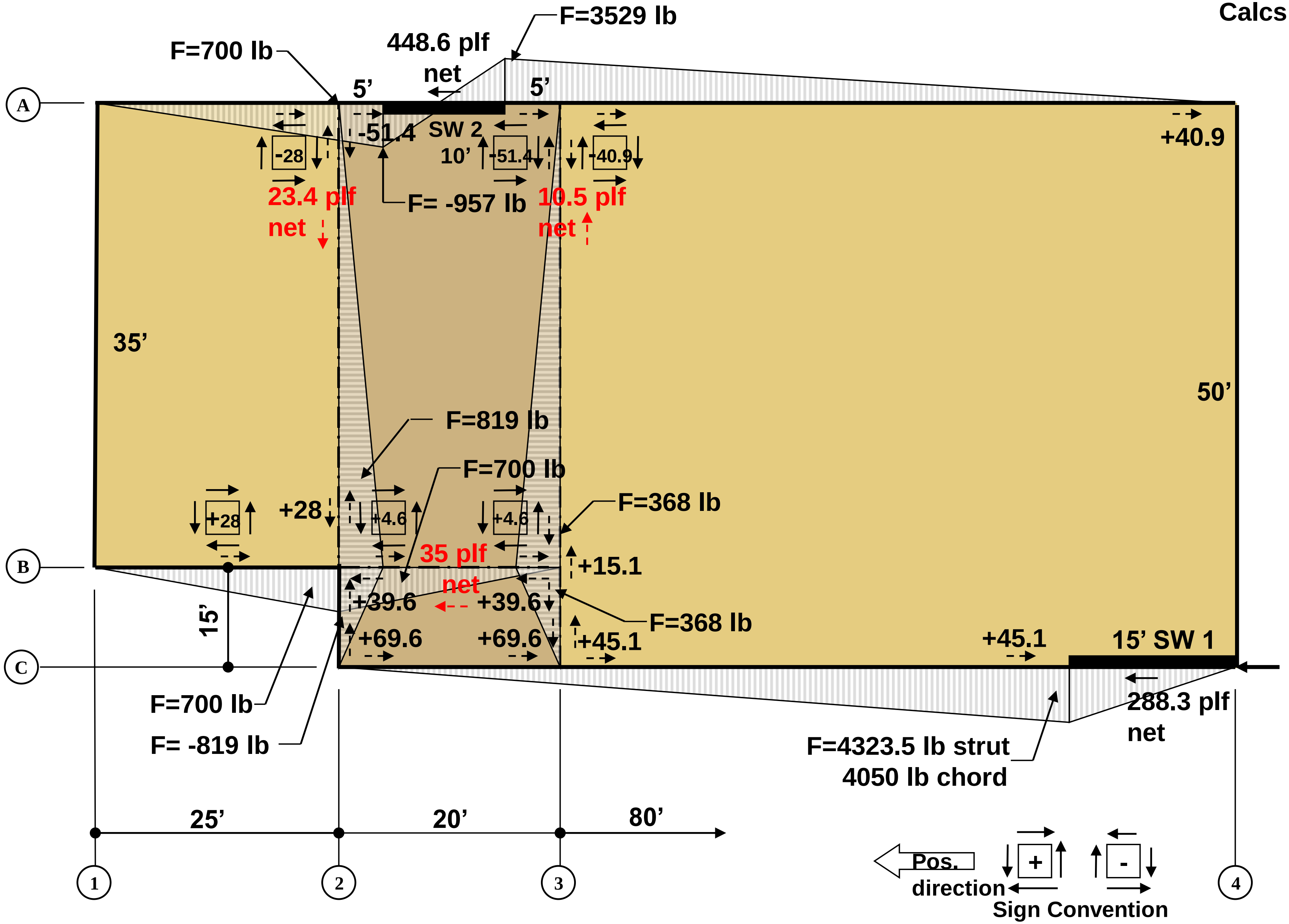
Example 2-Diaphragm with Horizontal End Offset -Longitudinal Loading



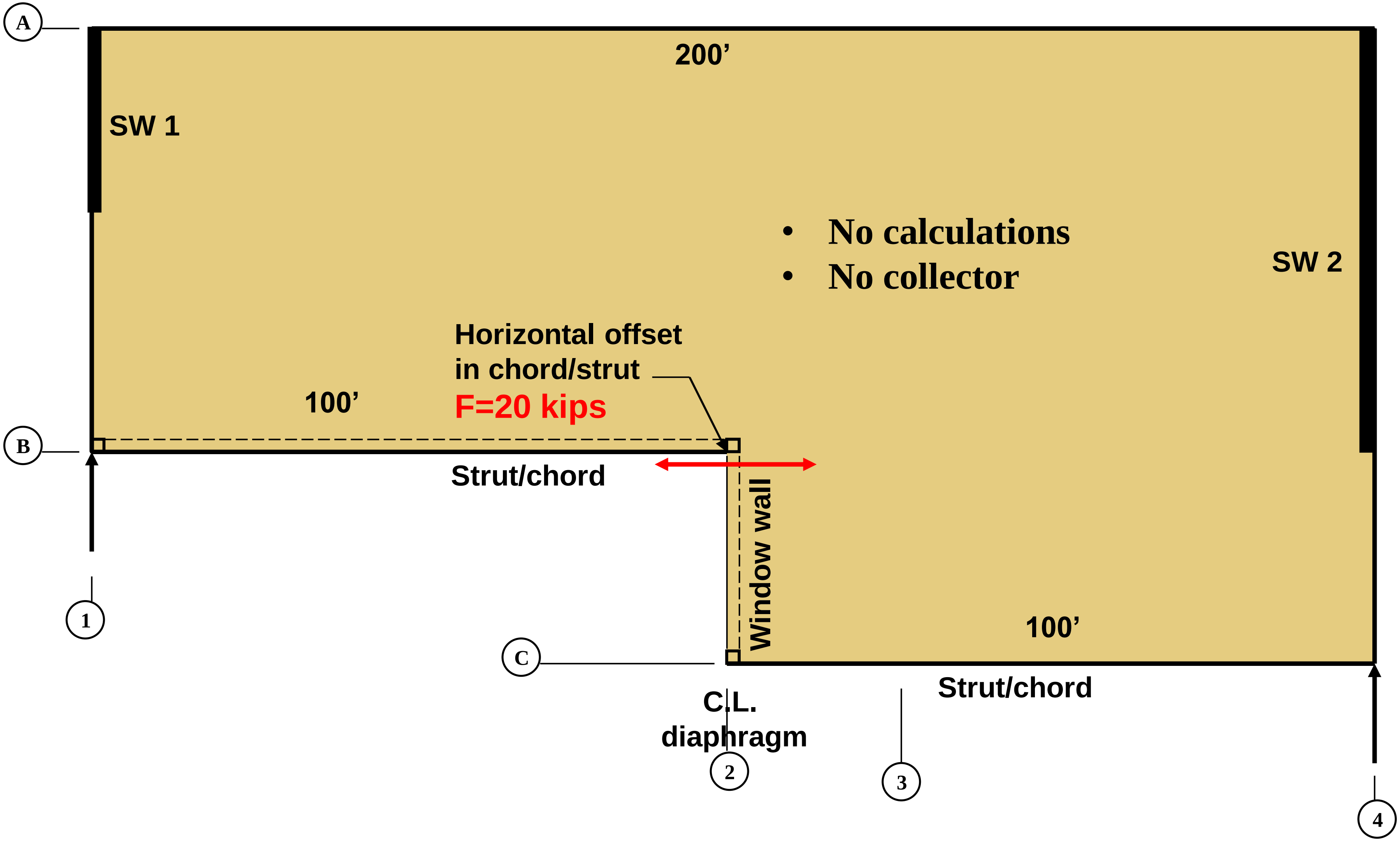
Calcs



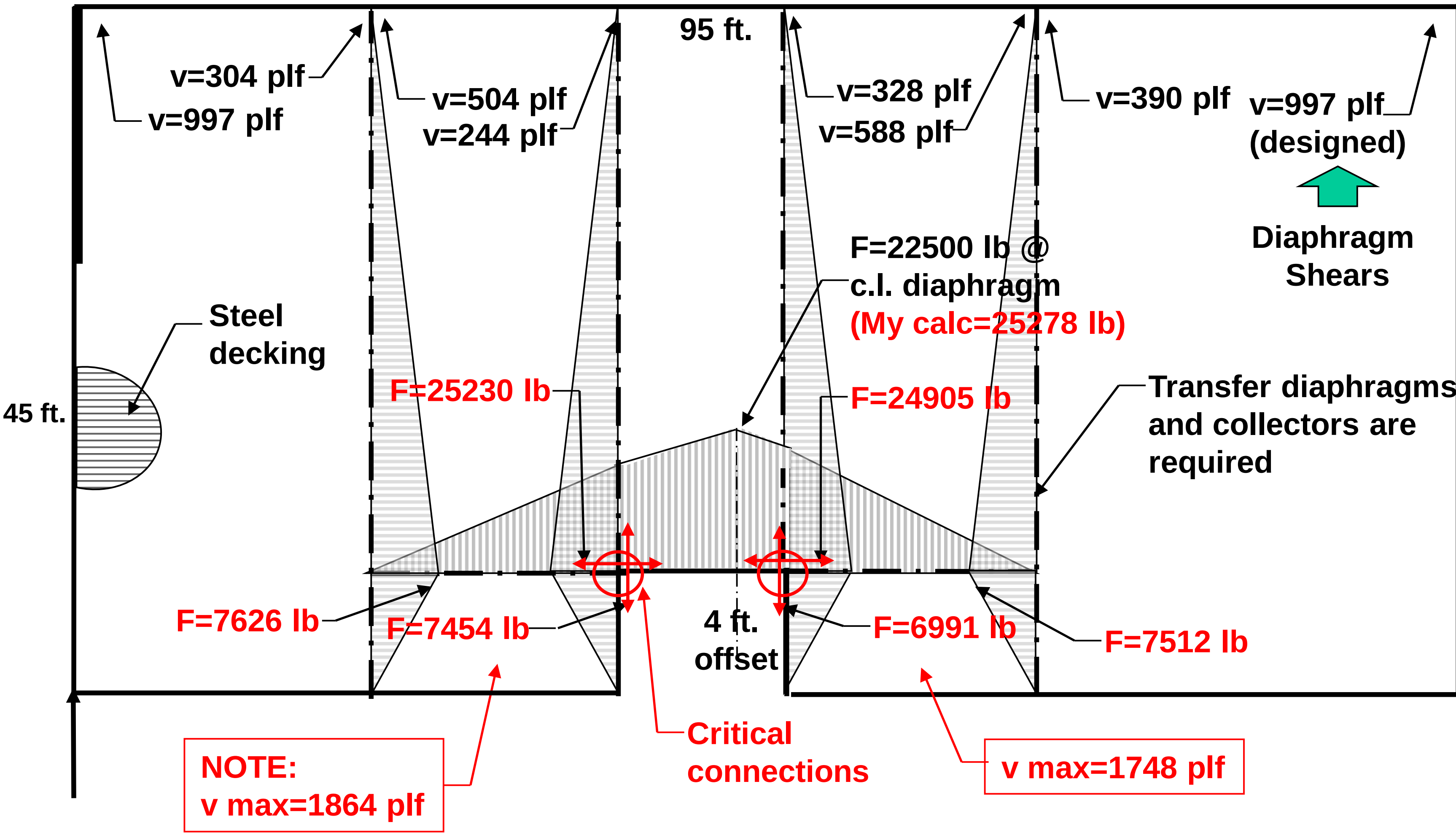
Transfer Diaphragm and Net Diaphragm Shear



Longitudinal and Transverse Collector/Strut Force Diagrams



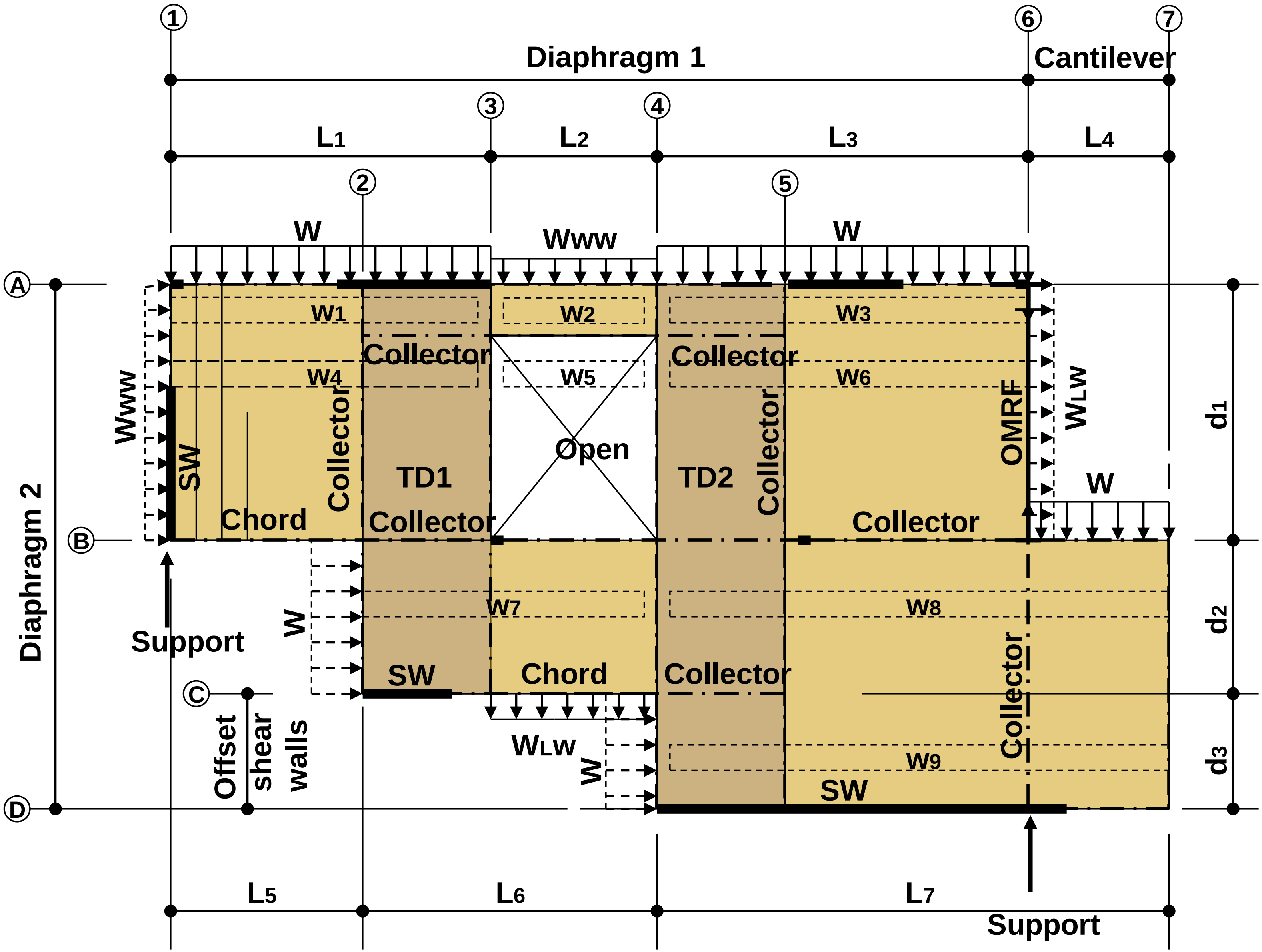
Example-Actual Project

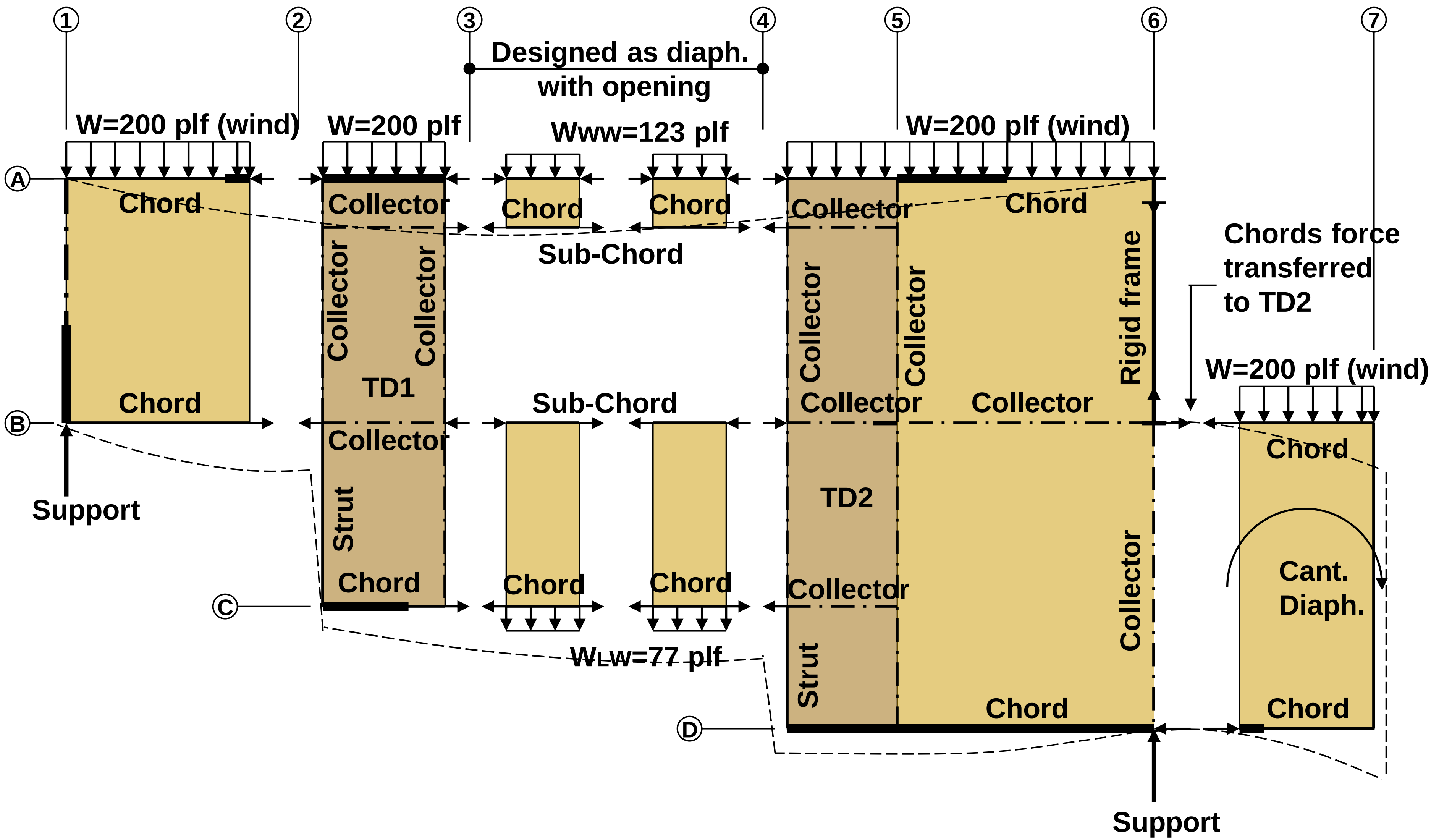


- Diaphragm designed as a simple rectangular diaphragm, no offset, using only a spreadsheet.
- Checked only diaphragm shear and chord force (maximum depth, not offset depth).
- <u>No collectors</u>, connection designs or details at re-entrant corners.
- Forces on trusses at collectors were not called out on drawing.

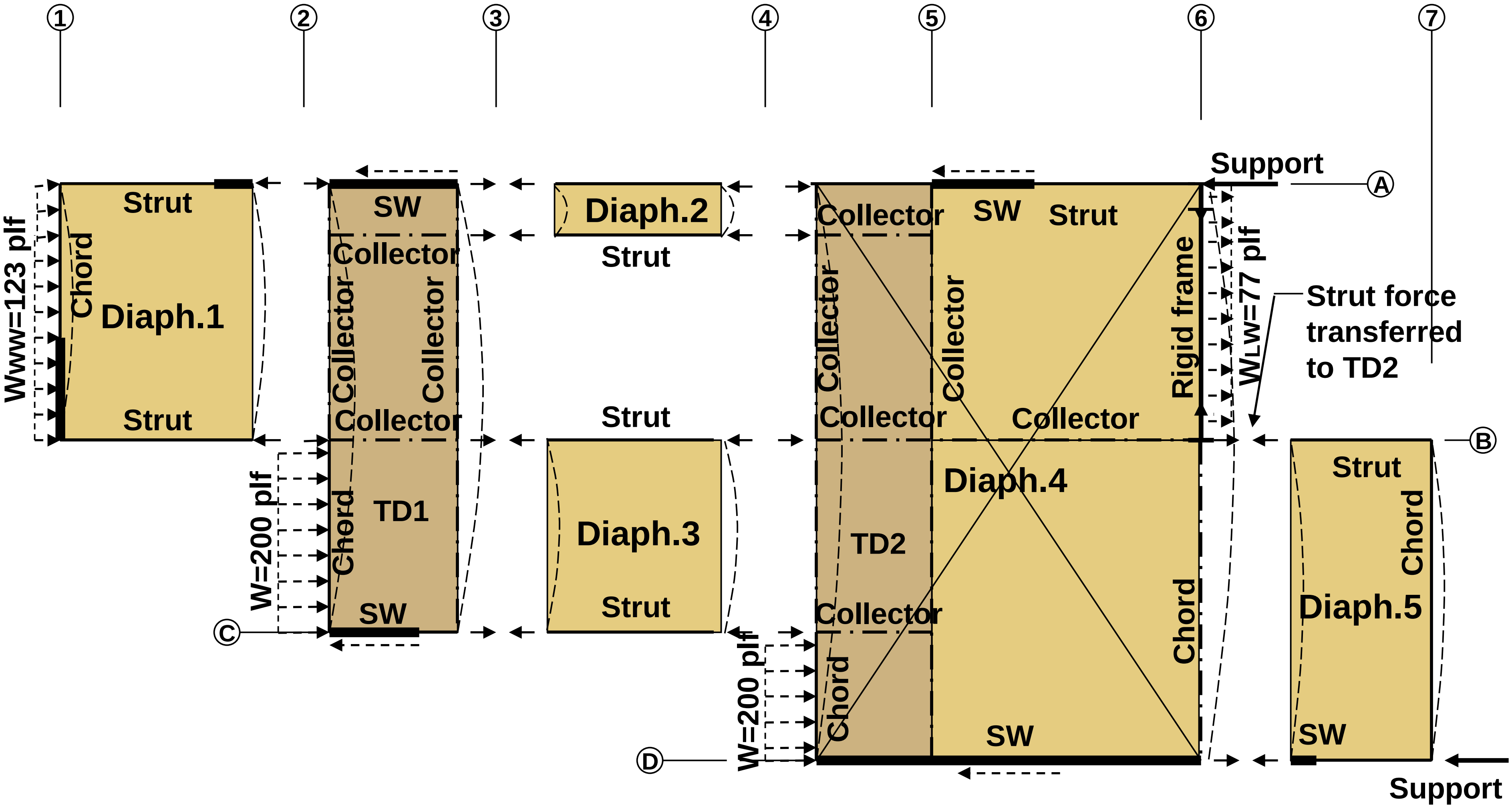
Example-Actual Project

A Quick Note on Segmentation

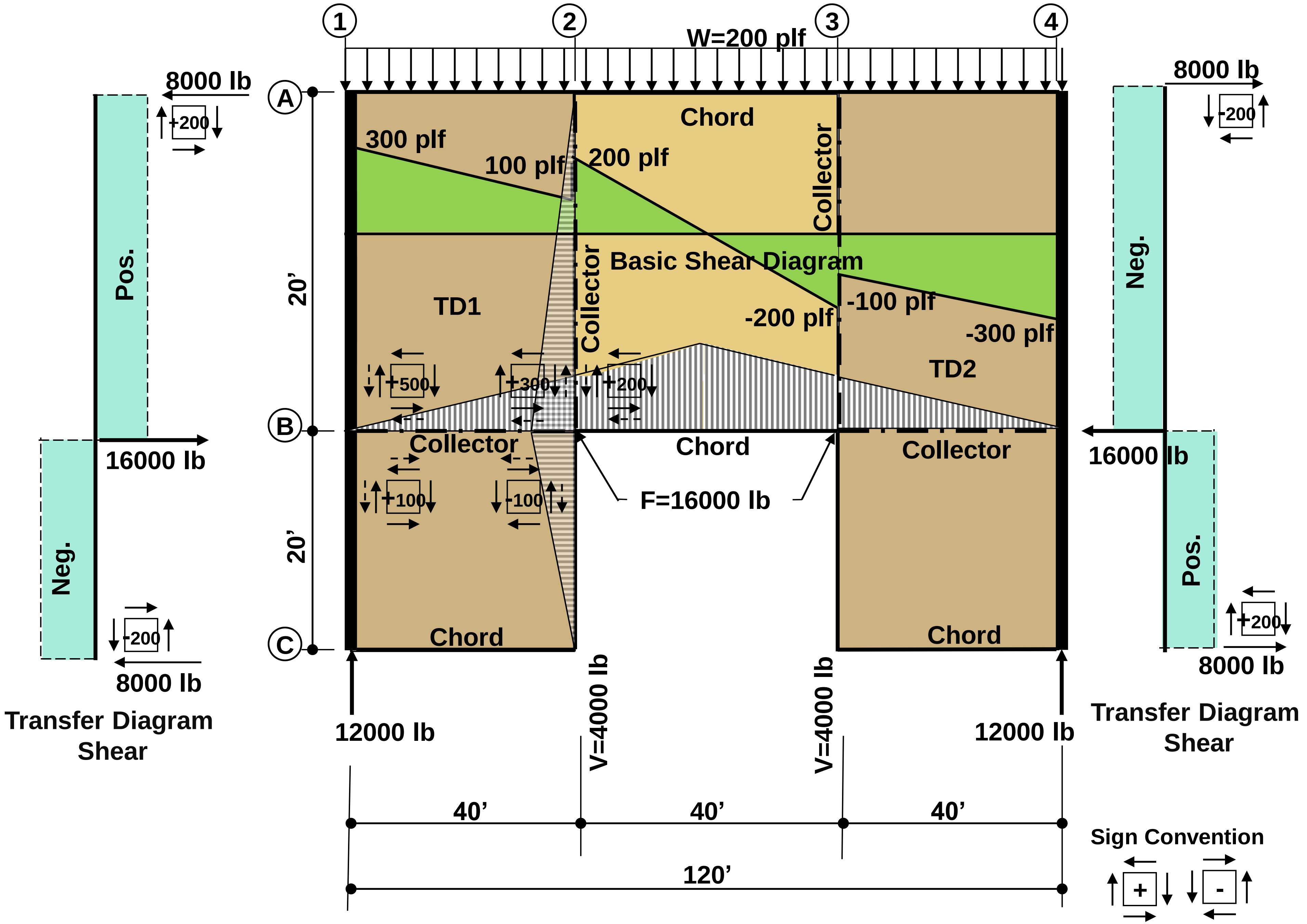




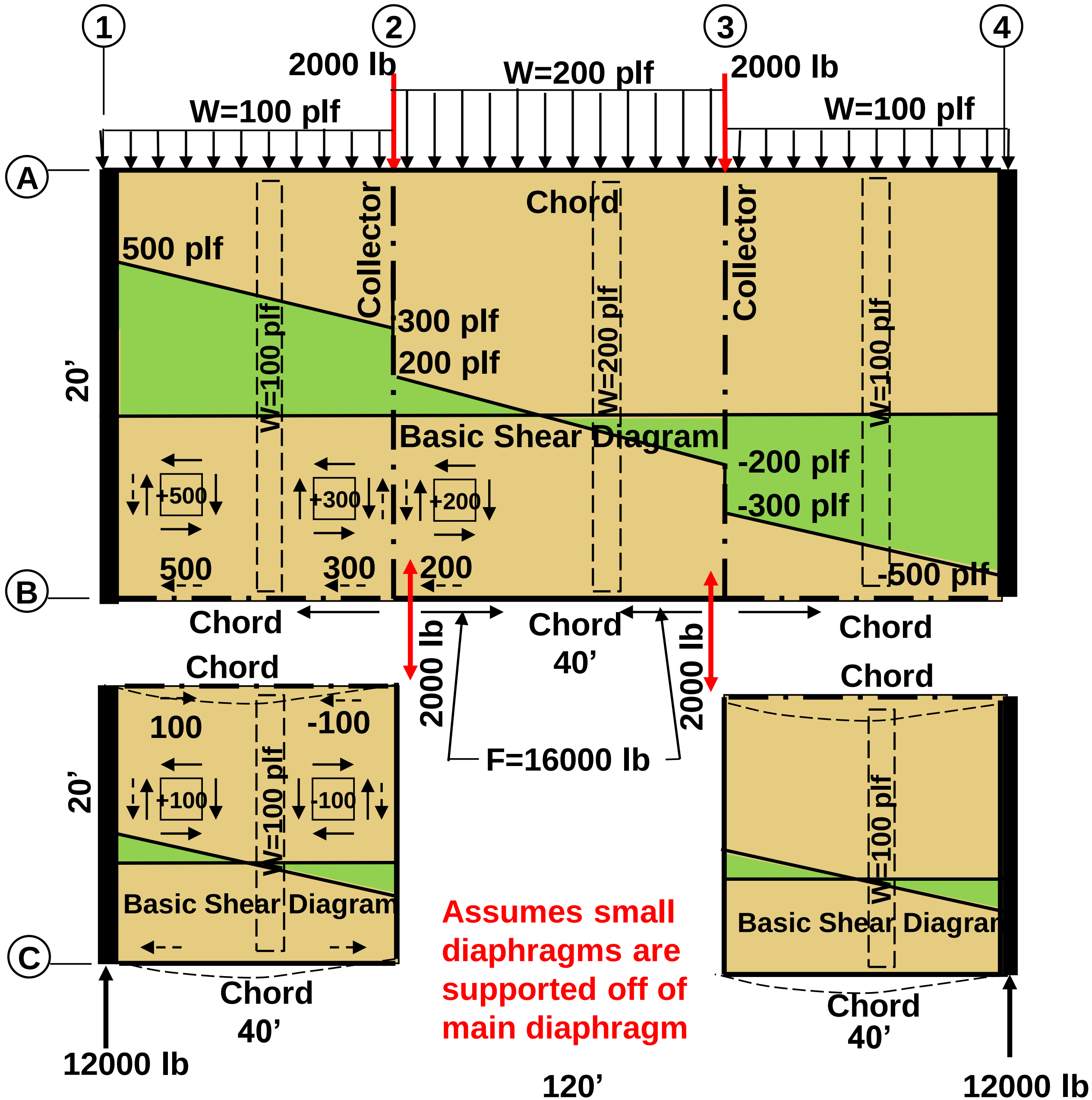
Segmentation of the Diaphragm for Transverse Loading



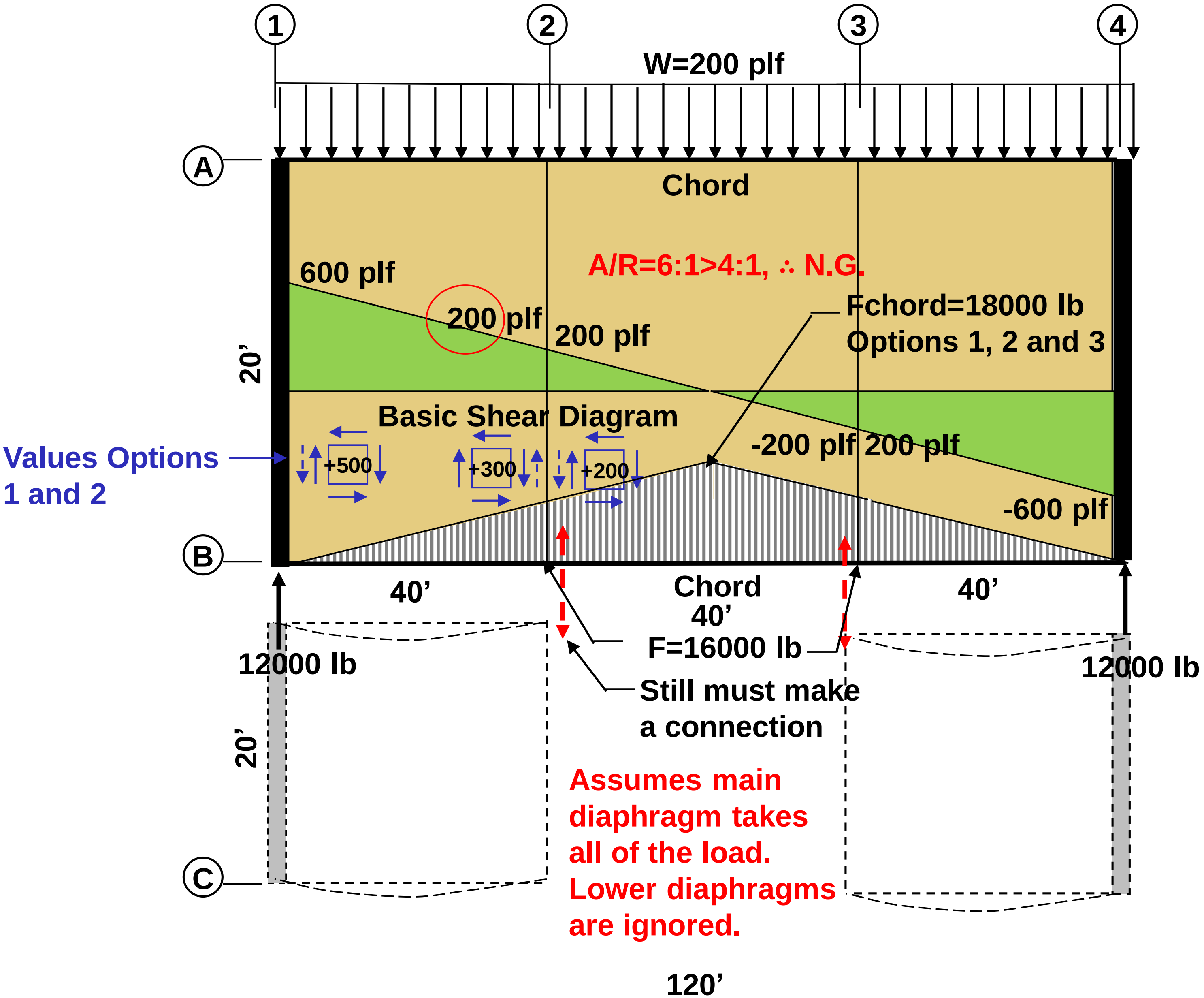
Segmentation of the Diaphragm for Longitudinal Loading



Analysis Option 1-Analyze as Diaphragm with Intermediate Offset



Analysis Option 2-Analyzing as separate diaphragms

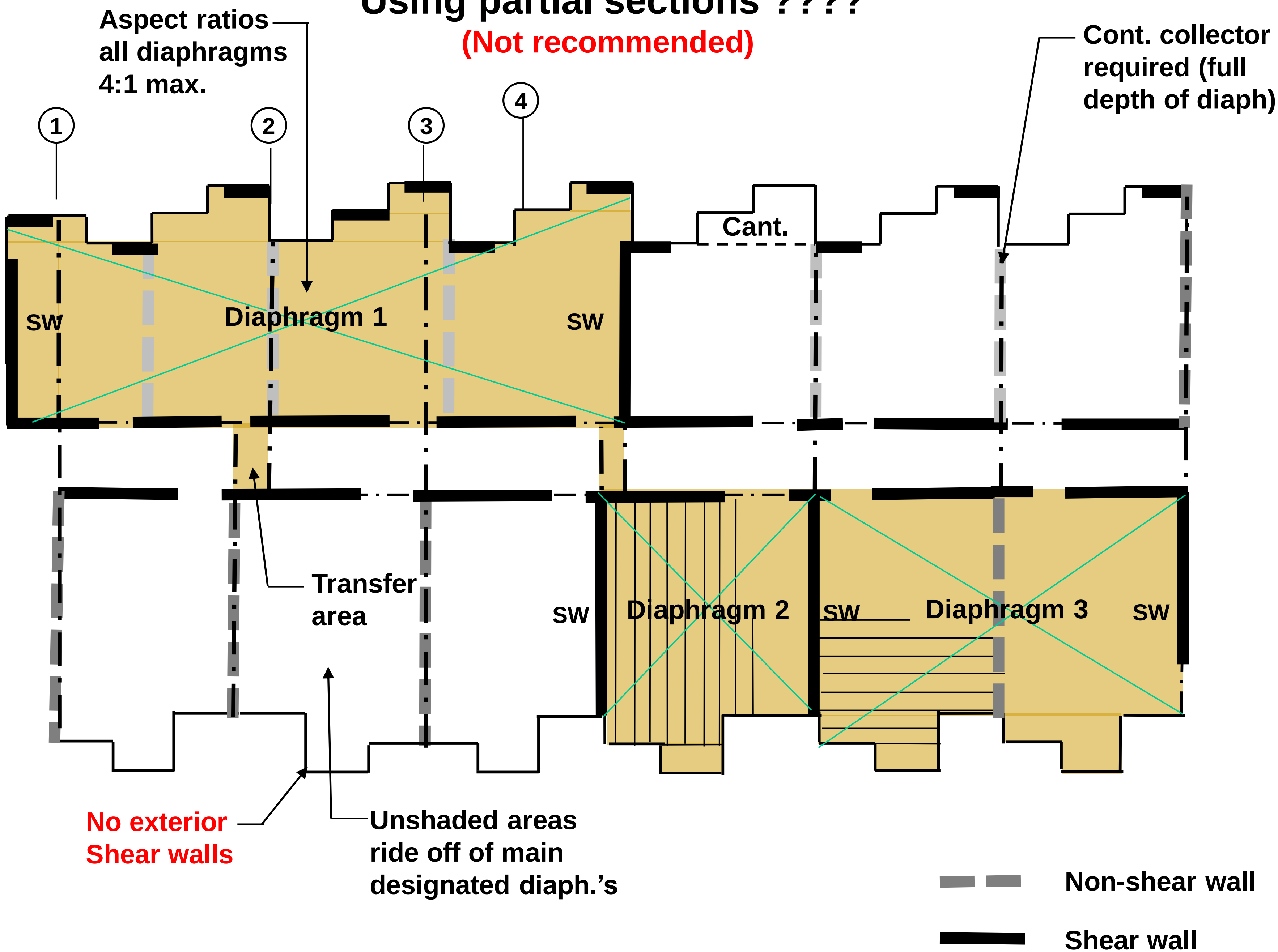


Analysis Option 3-Ignoring lower diaphragm sections

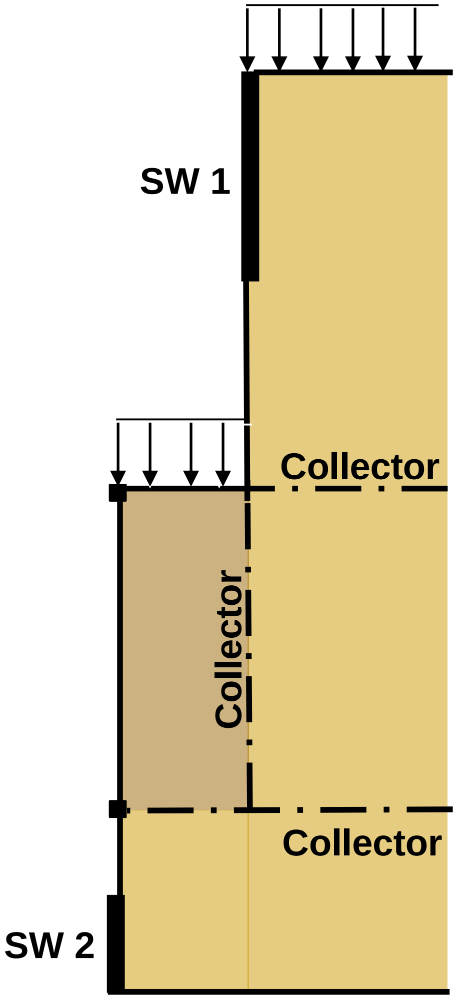
(Not recommended)

Using partial sections ????

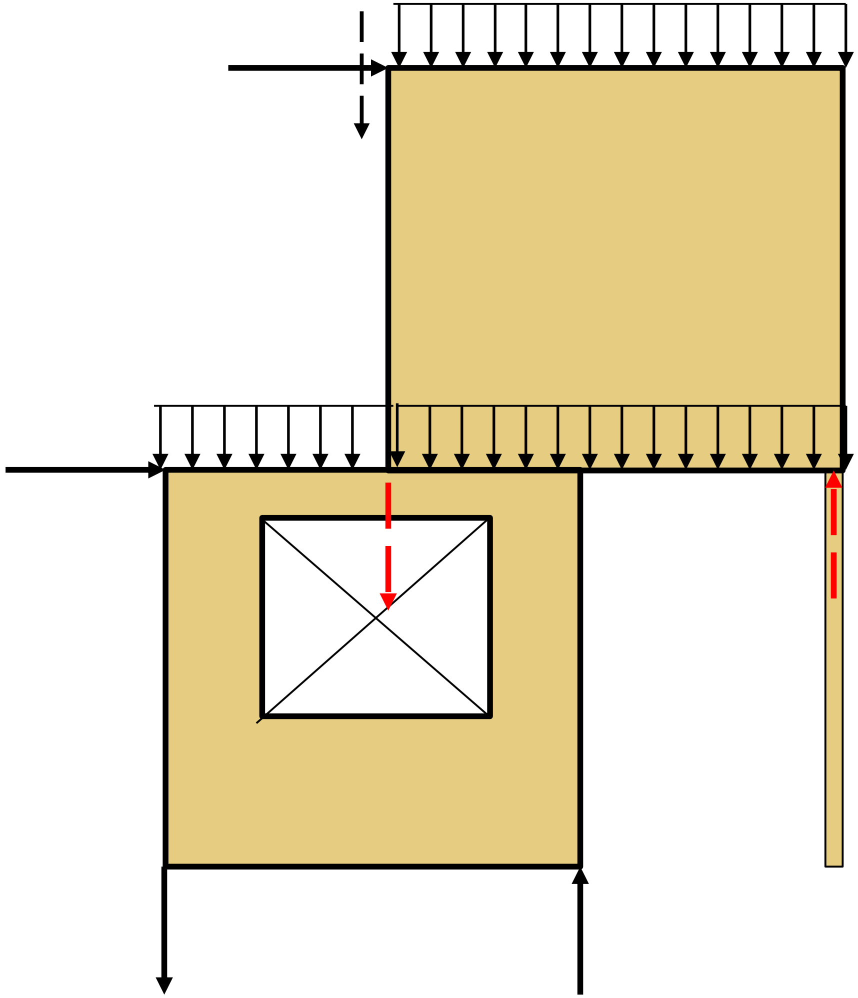
(Not recommended)



Offset Shear Walls



Out-of-plane Offsets



In-plane Offsets

Relevant Irregularities Per ASCE 7-10

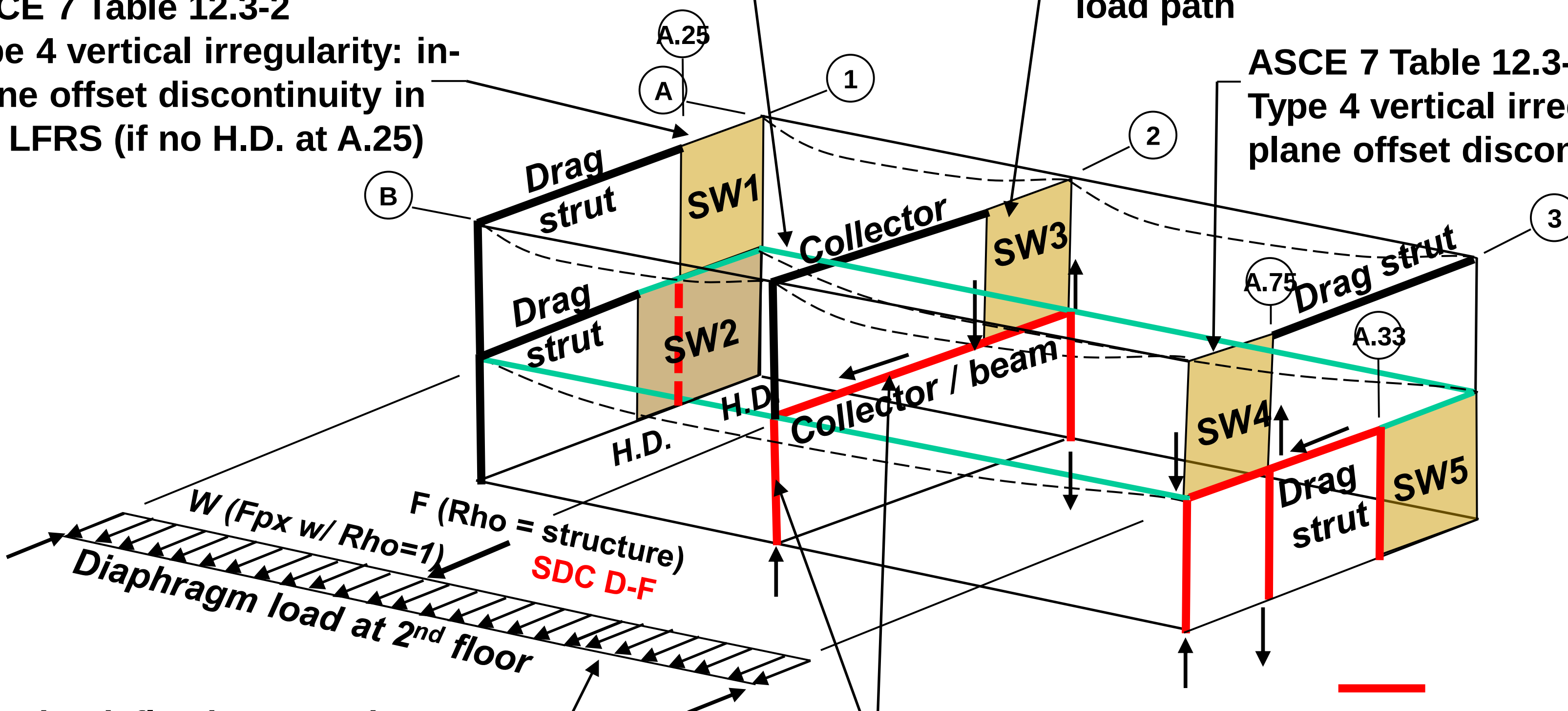
Horizontal Irregularities Table 12.3-1 and Vertical Irregularities Table 12.3-2

Transfer diaphragm grid line 1 to 3 See Section 12.10.1.1

ASCE 7 Table 12.3-1
Type 4 horizontal irregularity: out-of-plane offset discontinuity in the LFRS load path

ASCE 7 Table 12.3-2
Type 4 vertical irregularity: in-plane offset discontinuity in the LFRS (if no H.D. at A.25)

ASCE 7 Table 12.3-2
Type 4 vertical irregularity: in-plane offset discontinuity



The deflection equation must be adjusted to account for the uniformly distributed load plus the transfer force.

Potential buckling problem w/ supporting columns and beams

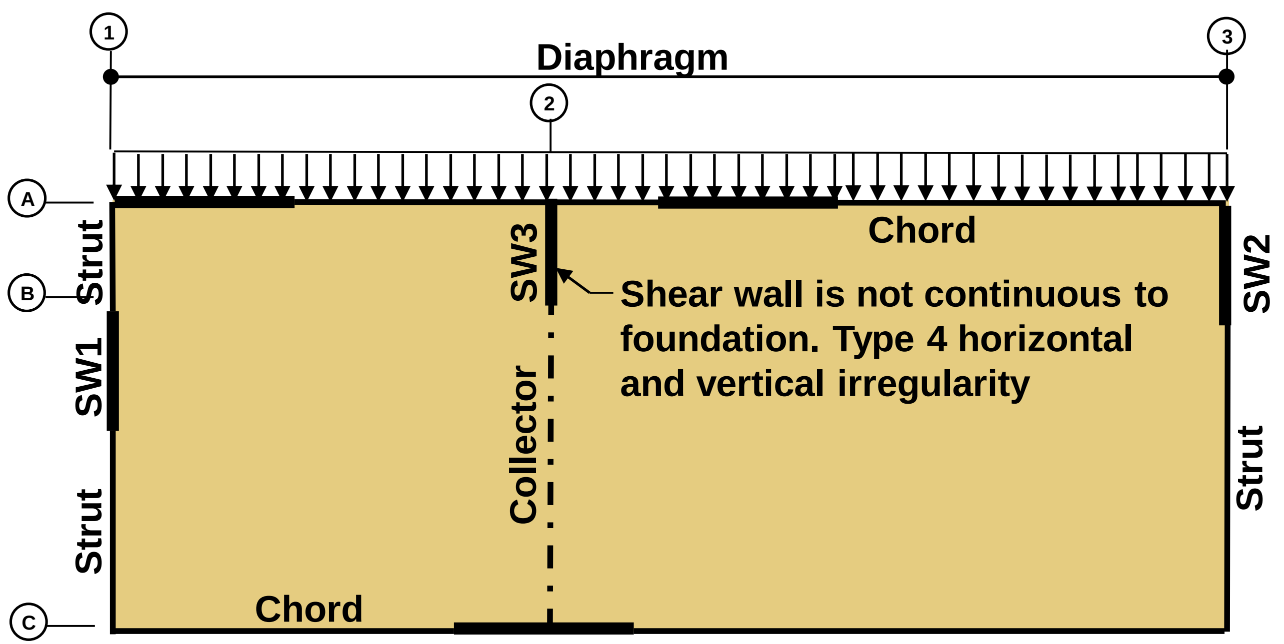
Elements requiring over-strength load combinations

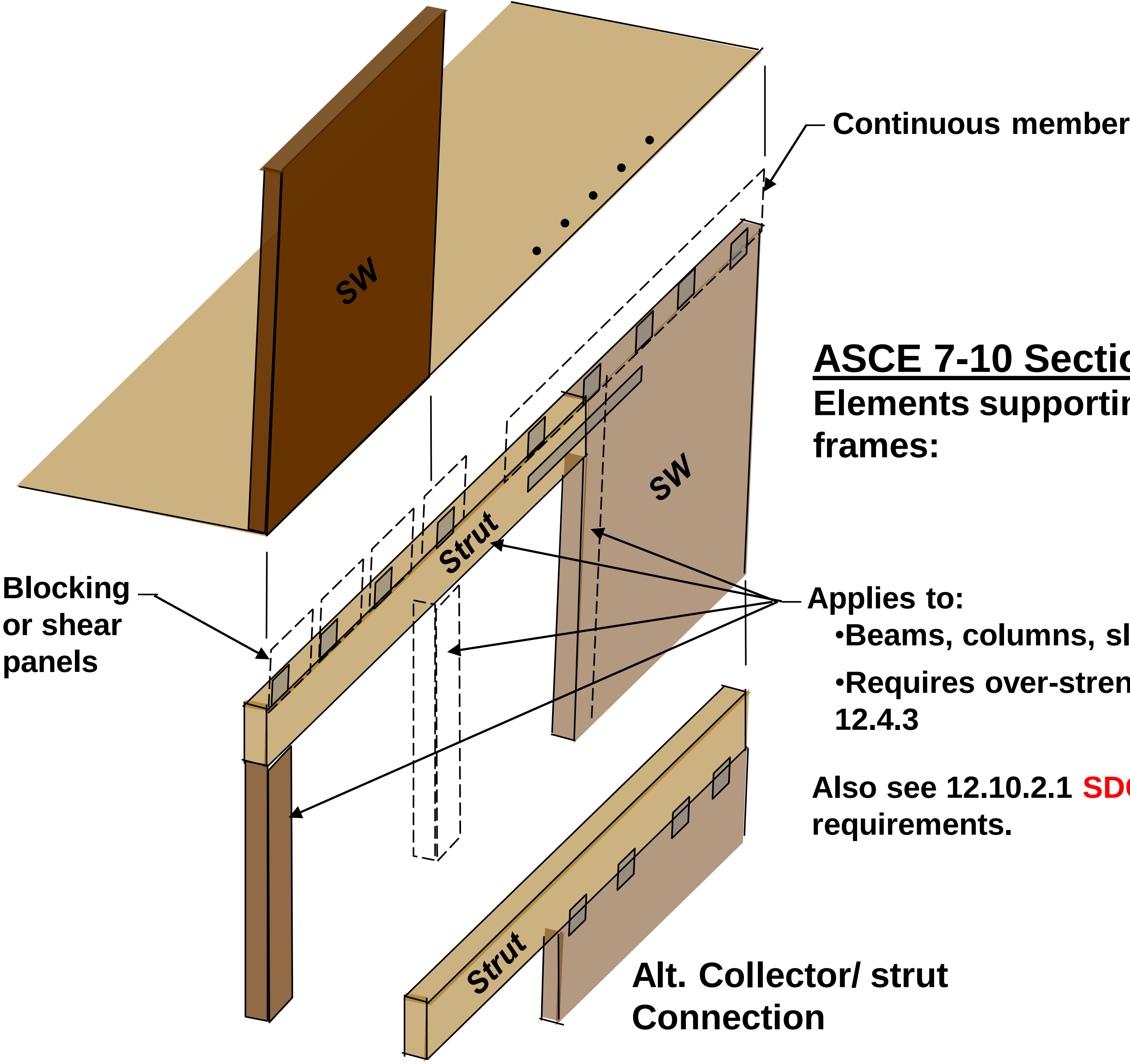
Type 4 Horizontal & Vertical Offset Irregularity-Seismic

Type 4 horizontal irregularity-Out-of-plane offset irregularity occurs where there is a discontinuity in lateral force resistance load path. Out-of-plane offset of at least one of the vertical lateral force resisting elements.

Type 4 vertical irregularity-In-plane discontinuity in vertical lateral force resisting element occurs where there is an offset of vertical seismic force resisting element resulting in overturning demands on a beam, column, truss, wall or slab.

- **ASCE 7-10 Section 12.3.3.3 (SDC B-F)**
  Elements supporting discontinuous walls or frames.
- **ASCE 7-10 Section 12.3.3.4 (SDC D-F)**
  Increases in force due to irregularity





ASCE 7-10 Section 12.3.3.3 (SDC B-F)

Elements supporting discont. Walls or frames:

Also see 12.10.2.1 SDC C-F for collector requirements.

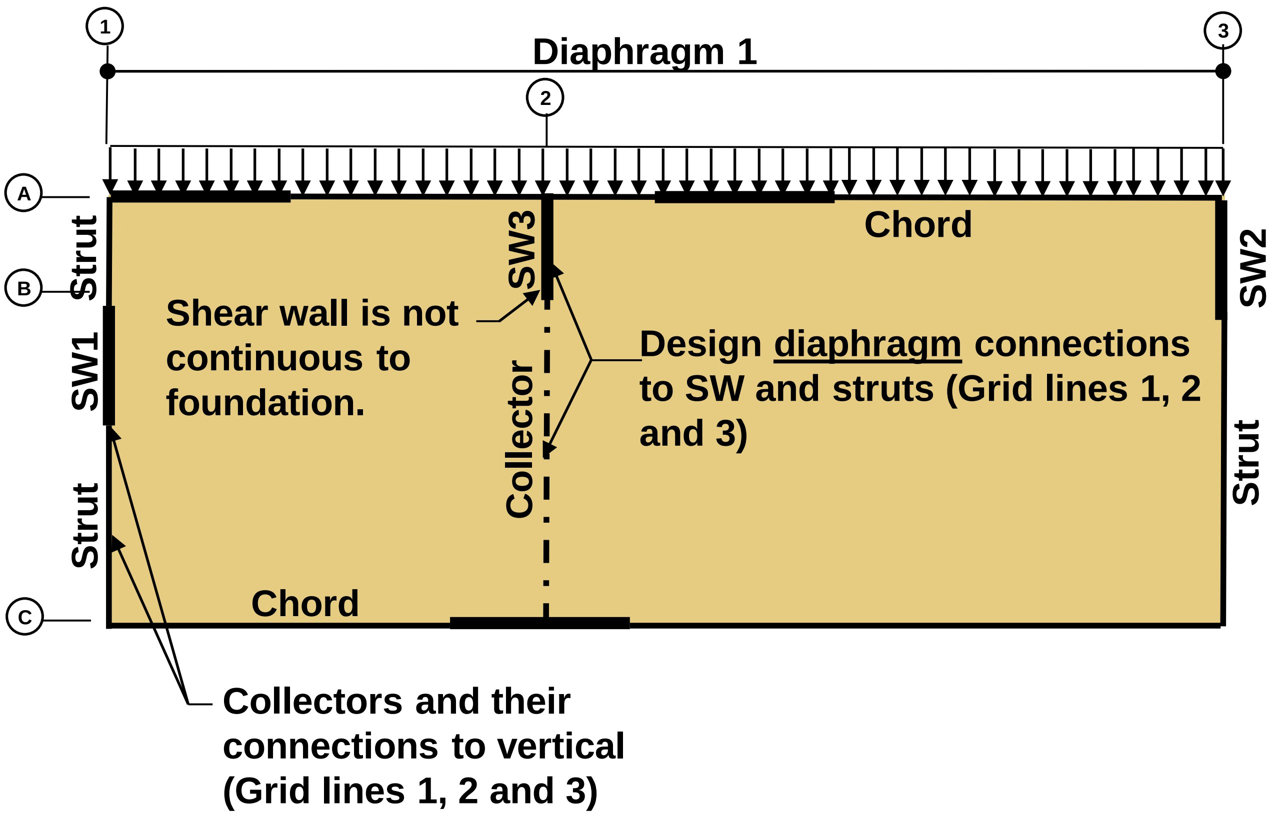
Type 4 Vertical Irregularity SDC D-F

(Interior collector similar)

ASCE 7-10 Section 12.3.3.4 (SDC D-F) -Type 4 Horizontal and Type 4 vertical irregularity requires a 25% increase in the diaphragm (inertial) design forces determined from 12.10.1.1 (Fpx) for the following elements:

- Connections of diaphragm to vertical elements and collectors.
- Collectors and their connections to vertical elements.

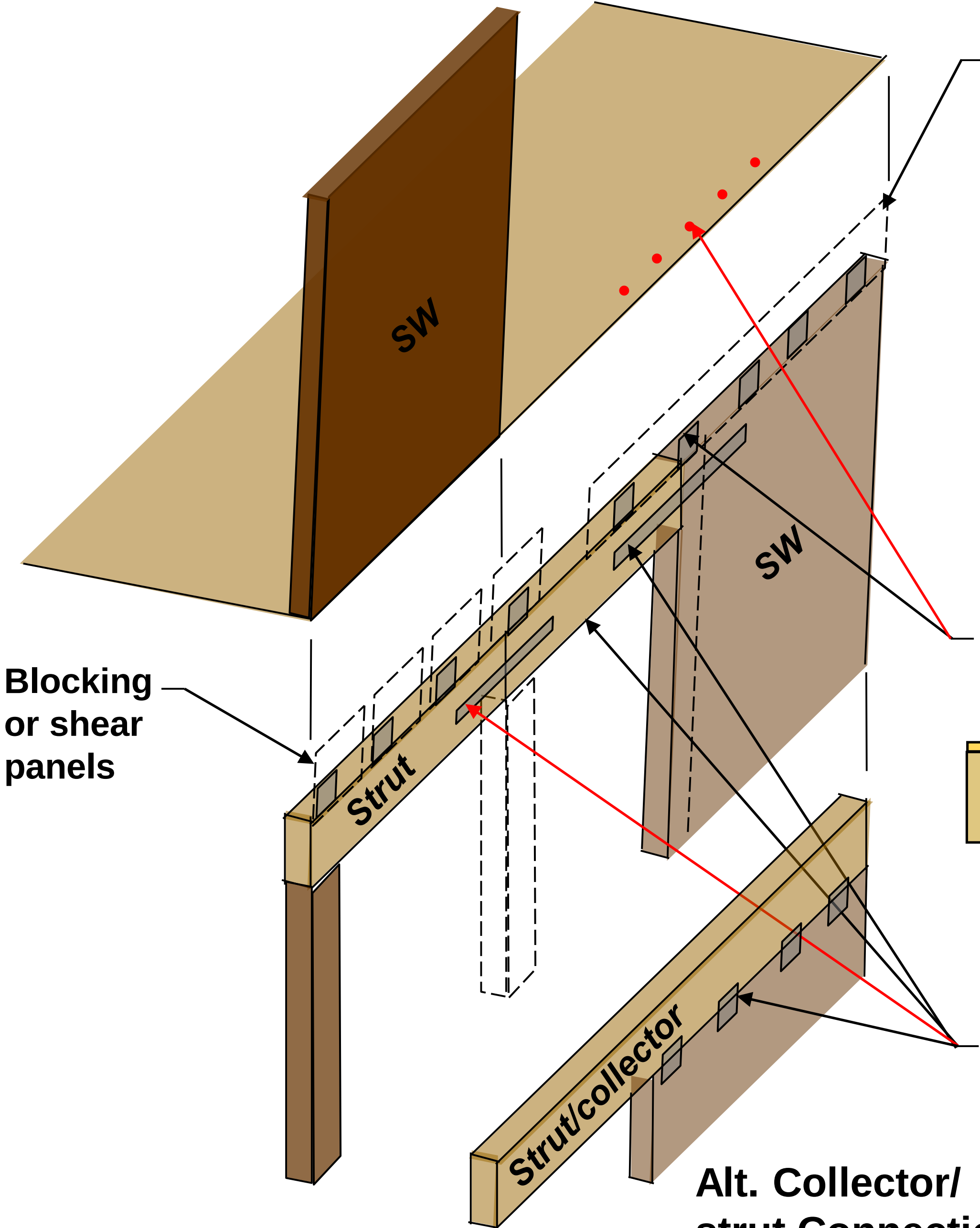
Exception: Forces using the seismic load effects including the over-strength factor of Section 12.4.3 need not be increased.



- Diaphragm shears are not required to be increased 25%.
- The transfer force (SW3) in SDC D-F must be increased by rho, per 12.10.1.1.

See 12.10.2 & 12.10.2.1 for collectors

Type 4 Horizontal Irregularity-Seismic

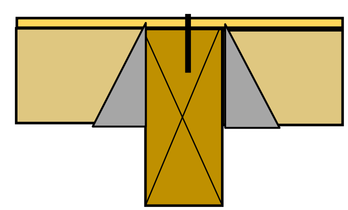


ASCE 7-10 Section 12.3.3.4 (SDC D-F)

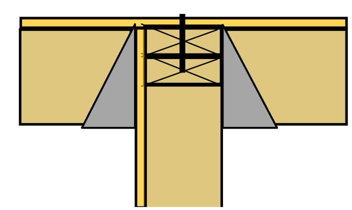
- Type 2 Horizontal Re-entrant corner Irregularity
- Type 3 Diaphragm discontinuity irregularity
- Type 4 horizontal or vertical irregularity:

Requires a 25% increase in the diaphragm design forces (Fpx) determined from 12.10.1.1 for the following elements:

- Connections of diaphragm to vertical elements and collectors.



Collector



Shear Wall

- Collectors and their connections, including their connections to vertical elements.

Type 2 Horiz., Type 3 Horiz., and Type 4 Vert. & Horiz. Irregularity SDC D-F

(Interior collector similar)

Struts and Collectors-Seismic

Struts / collectors and their connections shall be designed in accordance with ASCE 7-10 sections:

12.10.2 SDC B - Collectors can be designed w/o over-strength but not if they support discontinuous walls or frames.

12.10.2.1 SDC C thru F- Collectors and their connections, including connections to the vertical resisting elements require the over-strength factor of Section 12.4.3, except as noted:

Shall be the maximum of:

$\Omega_o F_x$ - Forces determined by ELF Section 12.8 or Modal Response Spectrum Analysis procedure 12.9

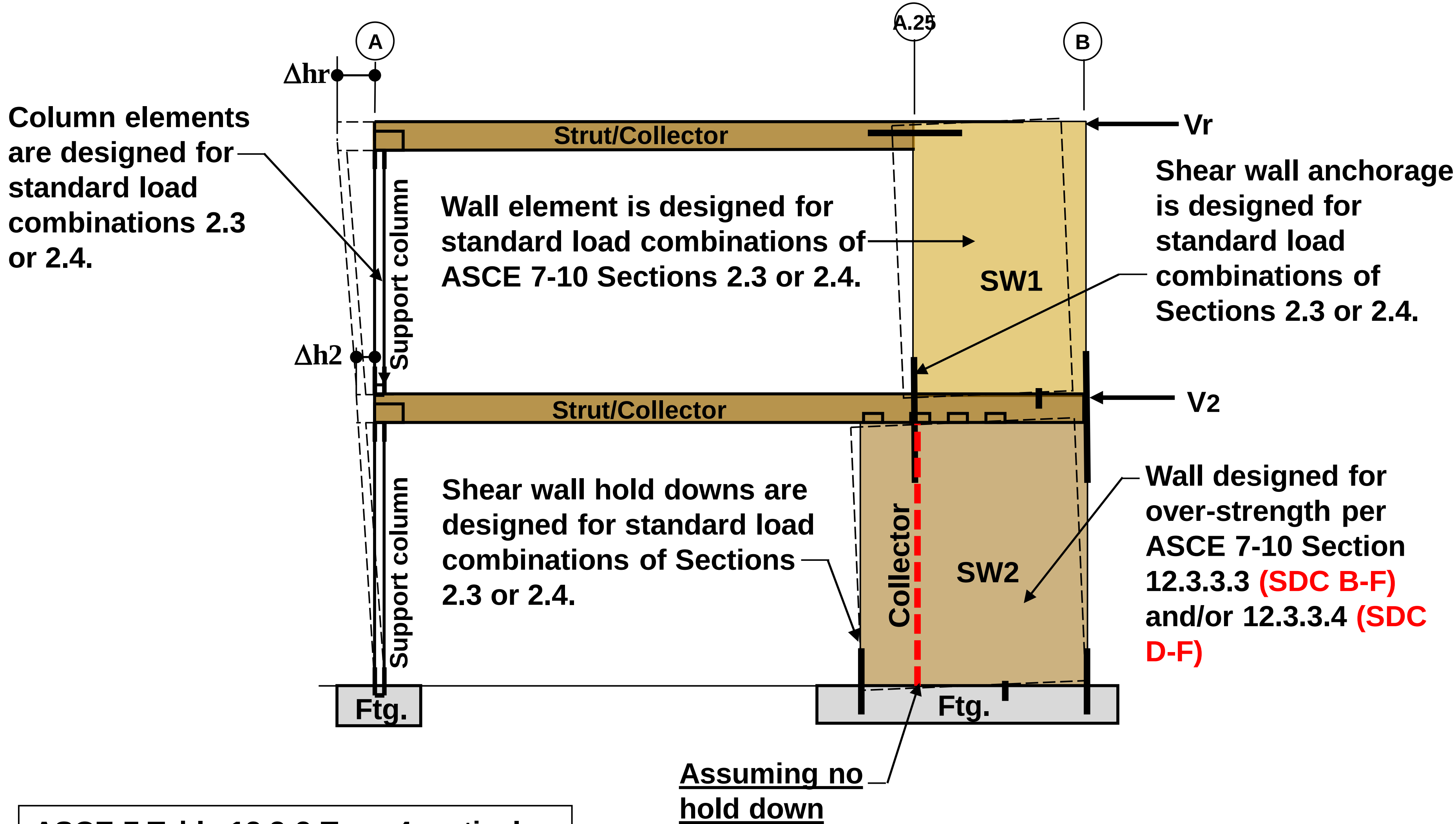
$\Omega_o F_{px}$ - Forces determined by Diaphragm Design Forces (Fpx), Eq. 12.10-1 or

$F_{px\,min} = 0.2 S_{DS} I_e w_{px}$ - Lower bound seismic diaphragm design forces determined by Eq. 12.10-2 (Fpx_{min}) using the Seismic Load Combinations of section 12.4.2.3 (w/o over-strength)-do not require the over-strength factor.

$F_{px\,max} = 0.4 S_{DS} I_e w_{px}$- Upper bound seismic diaphragm design forces determined by Eq. 12.10-2 (Fpx_{max}) using the Seismic Load Combinations of section 12.4.2.3 (w/o over-strength)-do not require the over-strength factor.

Exception:

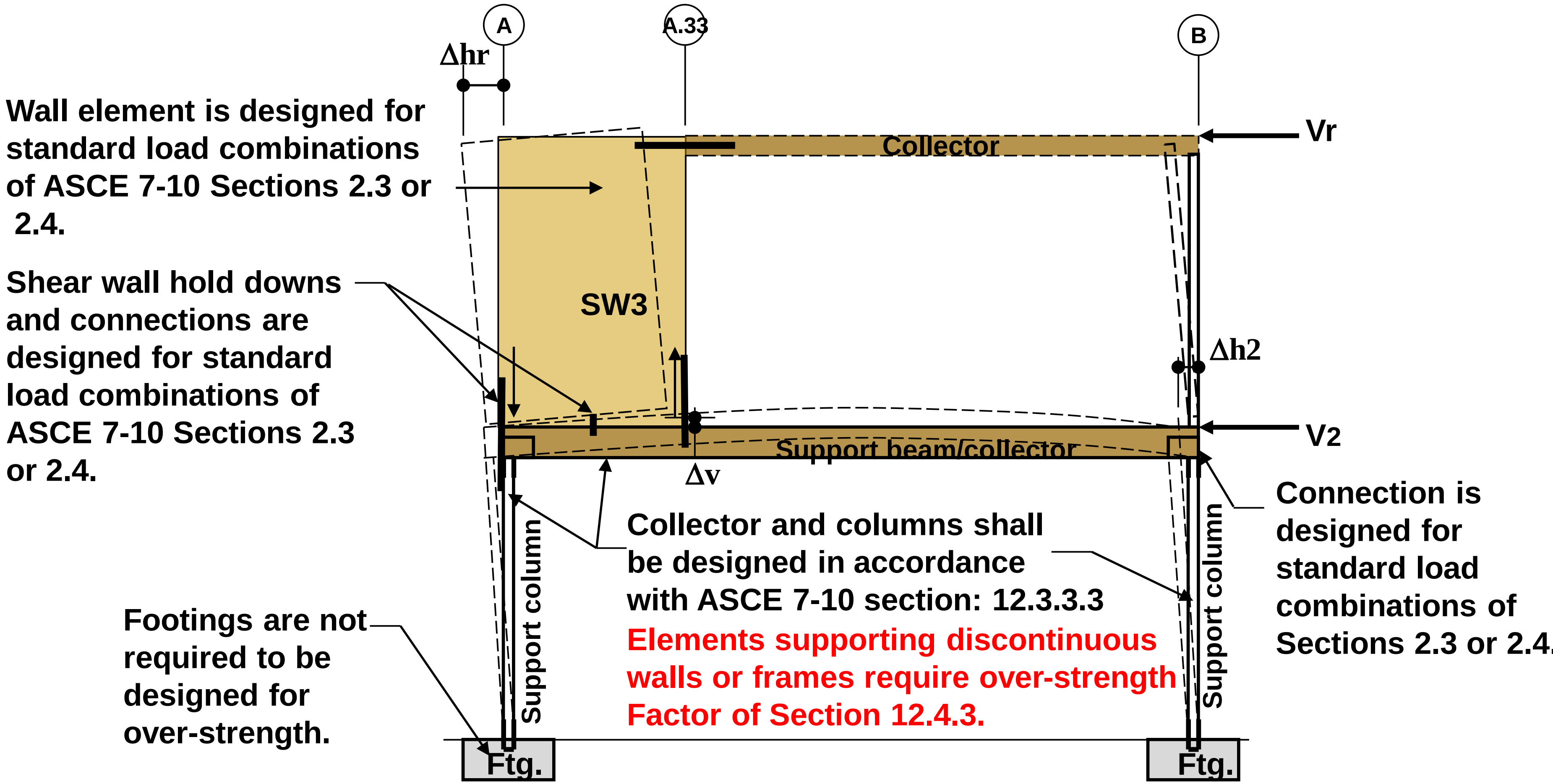
1. In structures (or portions of structures) braced entirely by light framed shear walls, collector elements and their connections, including connections to vertical elements need only be designed to resist forces using the standard seismic force load combinations of Section 12.4.2.3 with forces determined in accordance with Section 12.10.1.1 (Diaphragm inertial Design Forces, F_{px}).



ASCE 7 Table 12.3-2-Type 4 vertical irregularity- In-plane offset discontinuity in the LFRS

See struts and collectors

Shear wall system at grid line 1
In-plane Offset of Wall

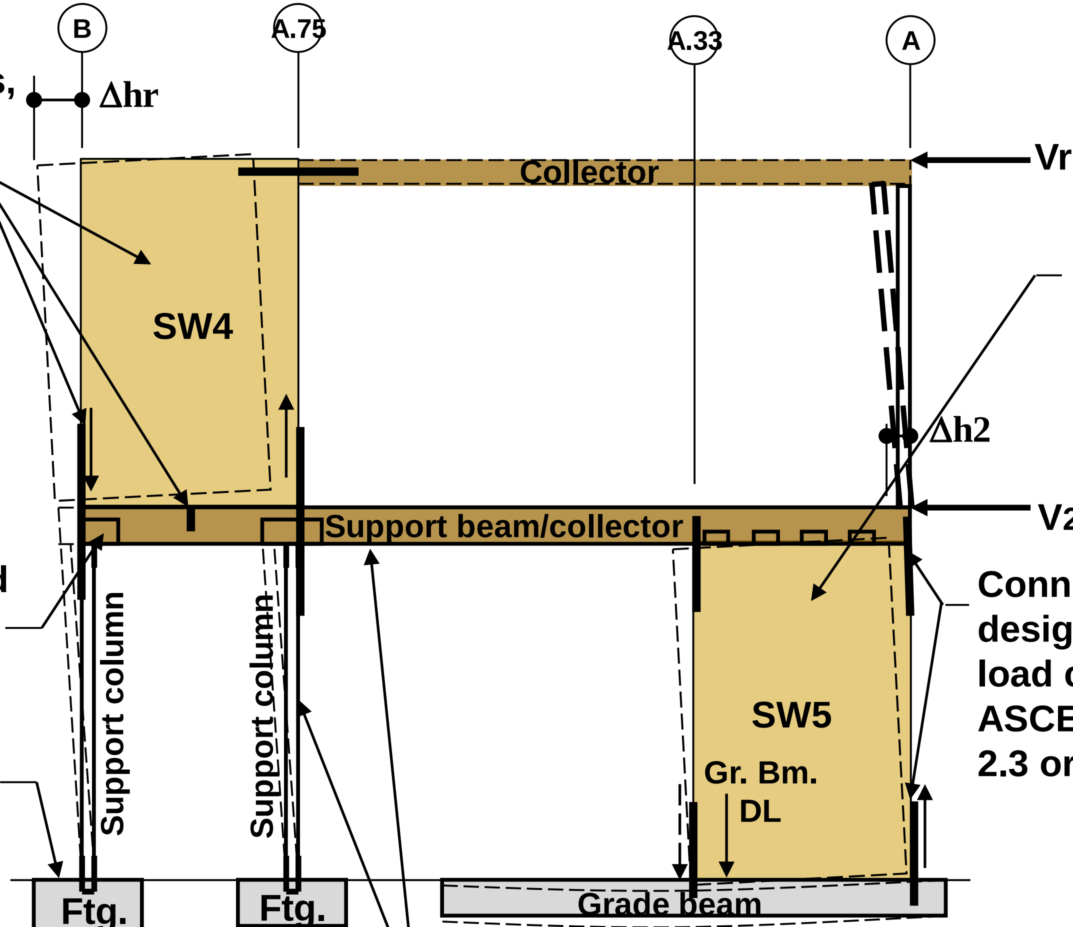


ASCE 7 Table 12.3-1-Type 4 horizontal irregularity- out of-plane offset discontinuity in the LFRS

See struts and collectors

Shear wall system at grid line 2
Out-of-Plane Offset

Wall element, hold downs, and connections are designed for standard load combinations of ASCE 7-10 Sections 2.3 or 2.4.



Wall element designed for standard load combinations of Sections 2.3 or 2.4.

Connections are designed for standard load combinations of Sections 2.3 or 2.4.

Connections are designed for standard load combinations of ASCE 7-10 Sections 2.3 or 2.4.

Footings are not required to be designed for over-strength.

Collector and columns shall be designed in accordance with ASCE 7-10 section: 12.3.3.3

Elements supporting discontinuous walls or frames require over-strength factor of Section 12.4.3.

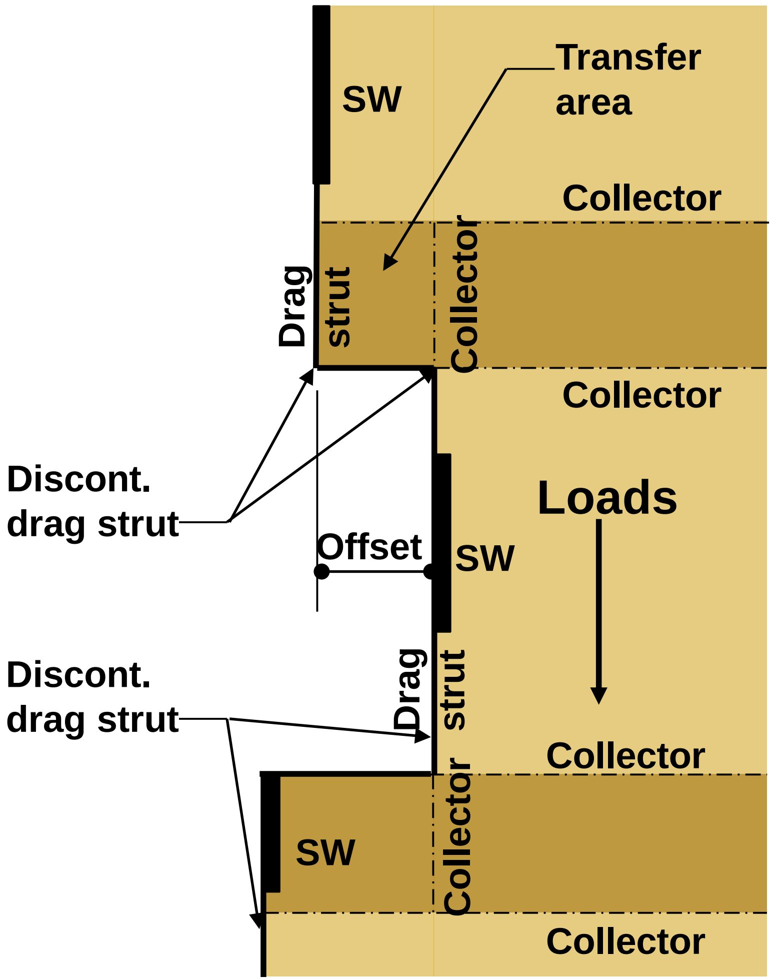
ASCE 7 Table 12.3-2-Type 4 vertical irregularity- In-plane offset discontinuity in the LFRS

See struts and collectors

Shear wall system at grid line 3-In-plane Offset

Out-of-Plane Offset Shear Walls

Assumed to act in the Same Line of Resistance



Typical mid-rise multi-family structure at exterior wall line

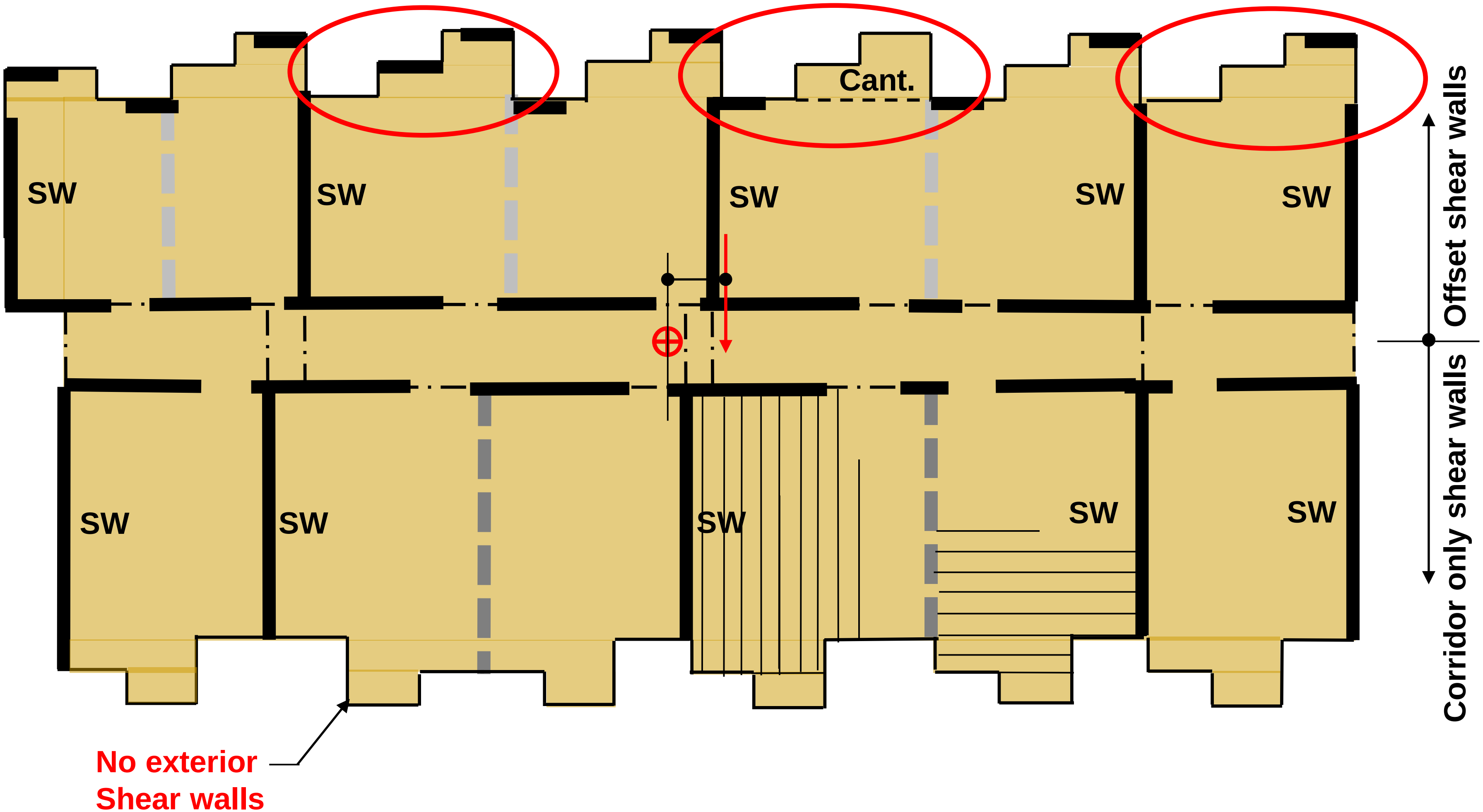
- Offset walls are often assumed to act in the same line of lateral-force-resistance.
- Calculations are seldom provided showing how the walls are interconnected to act as a unit, or to verify that a complete lateral load path has been provided.
- Collectors are required to be installed to transfer the disrupted forces across the offsets.

~~ASCE 7-10 Section 14.5.2~~

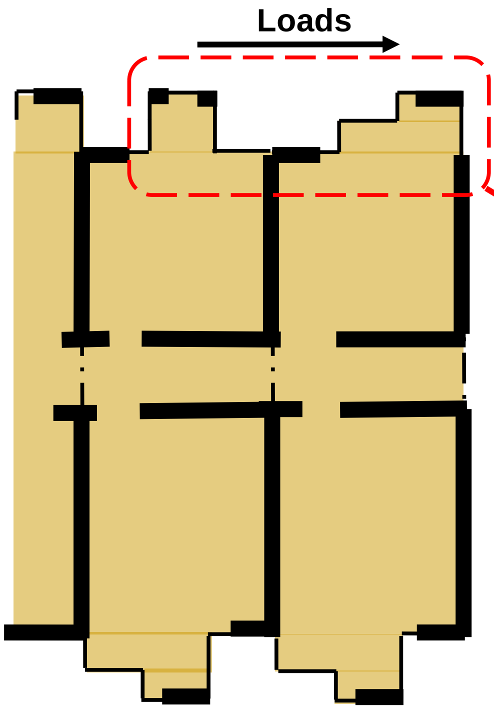
Where offset walls occur in the wall line, the shear walls on each side of the offset should be considered as separate shear walls unless provisions for force transfer around the offset are provided. ← In the plane of the diaphragm

Check for Type 2 horizontal irregularity
Re-entrant corner irregularity

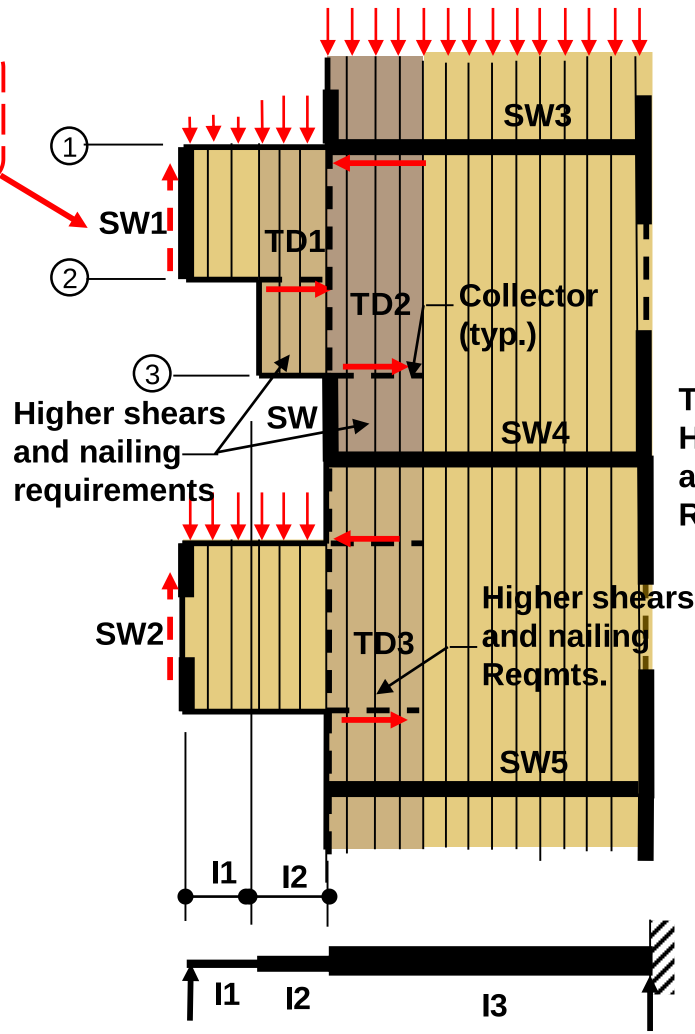
Mid-rise Multi-family



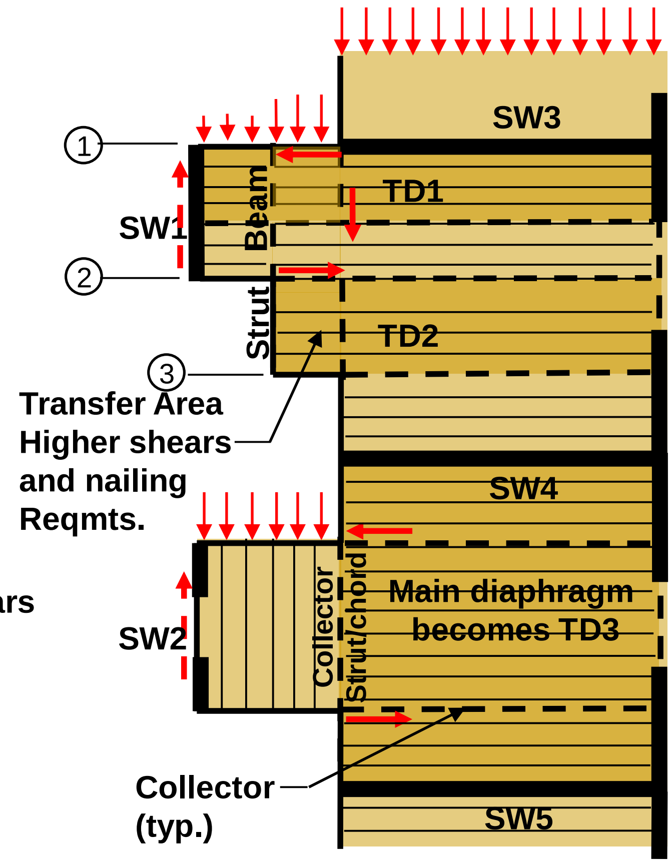
Flexible, semi-rigid, or rigid???



Multi Story, Multi-family Wood Structure



Diaphragm stiffness changes



Optional Framing Layouts

<u>ASCE7-10</u>

1.3.5 - Cont. ld. Paths

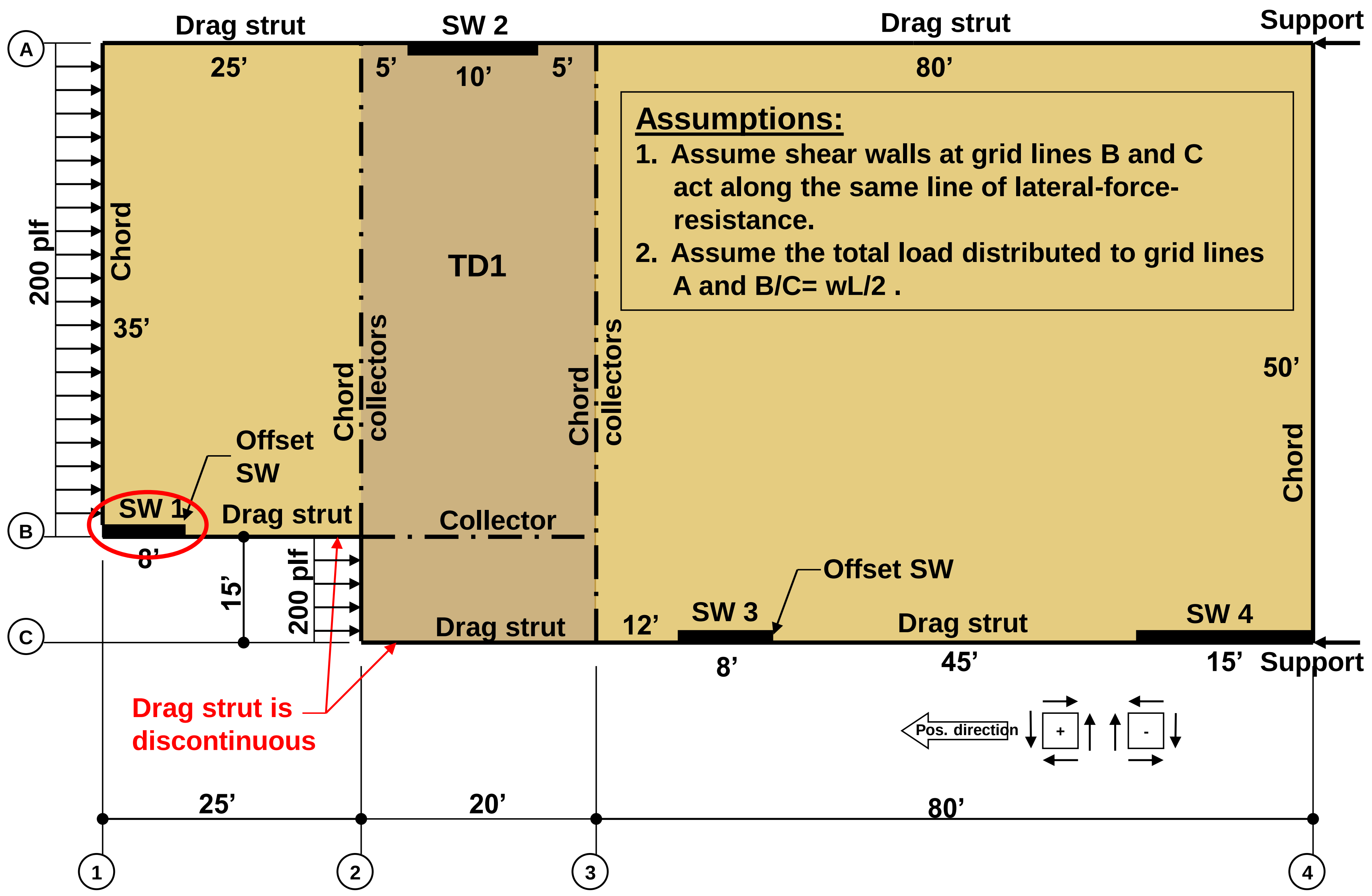
12.1.3 - Cont. ld. paths-inter-conn. Ties

12.10.1-Openings, re-entrant. –transfer of dis-cont. forces combined with other forces

12.10.2-Collector elements

Example 3-Diaphragm with Horizontal End Offset

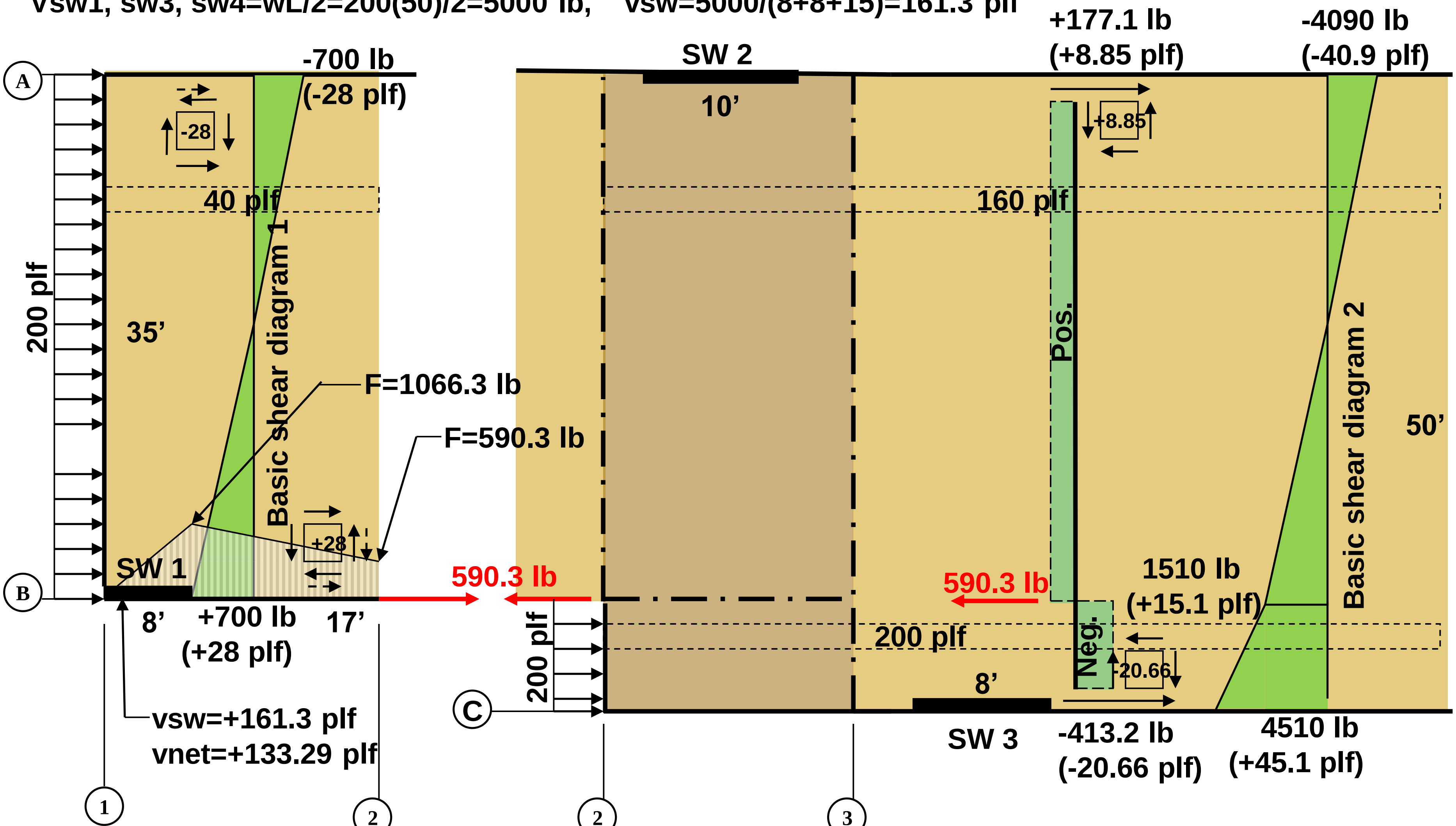
Longitudinal Loading-Out-of-plane offset Shear Walls



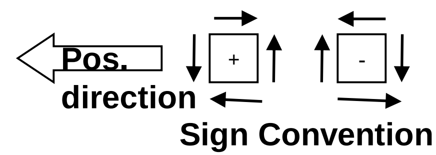
Total Shear to Shear Walls (Assumed)

Vsw2=wL/2=200(50)/2=5000 lb,   vsw2=5000/10=500 plf

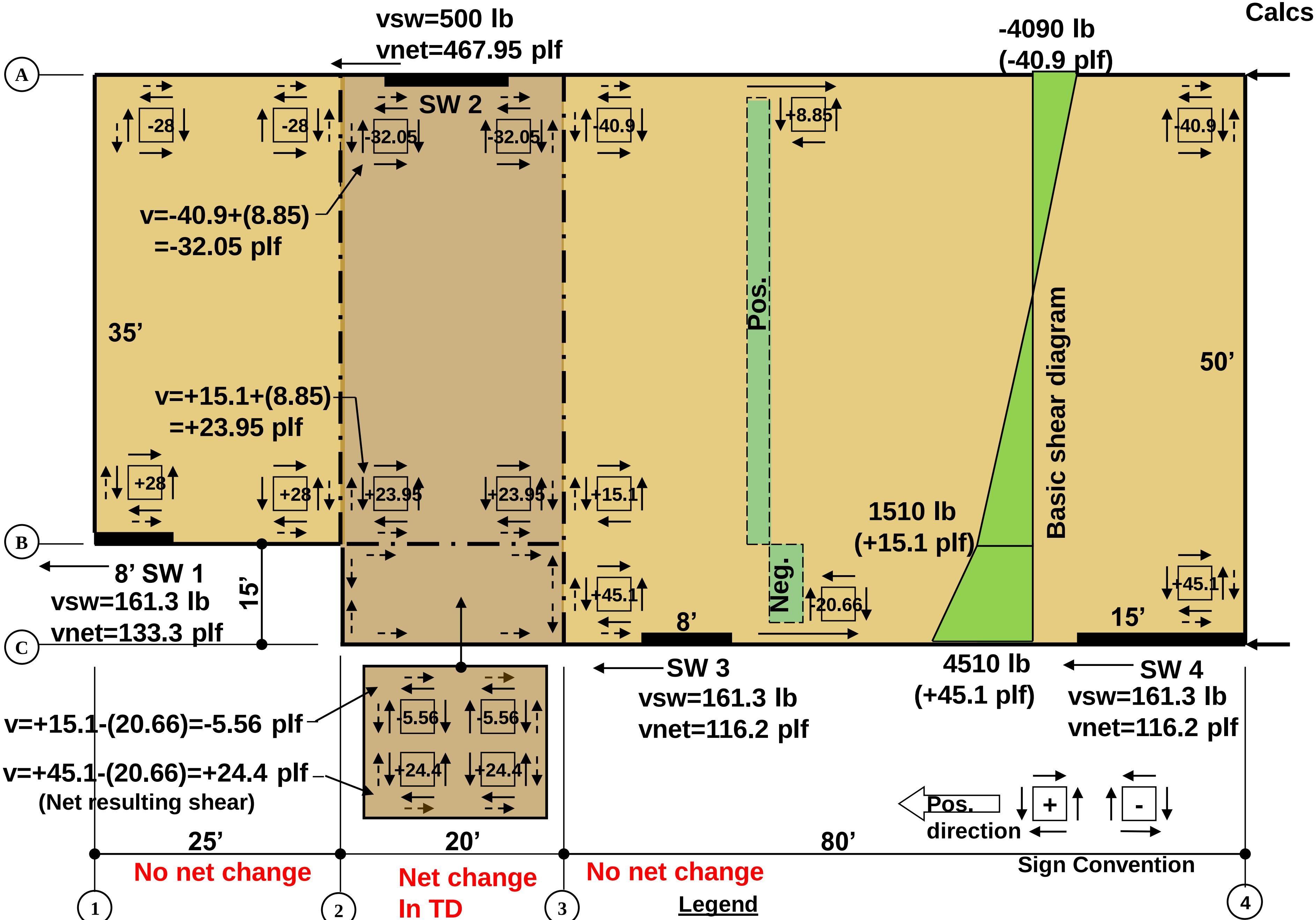
Vsw1, sw3, sw4=wL/2=200(50)/2=5000 lb,   vsw=5000/(8+8+15)=161.3 plf



Determine Force transferred
Into Transfer Diaphragm



Basic Diaphragm Shears and Transfer Diaphragm Shear



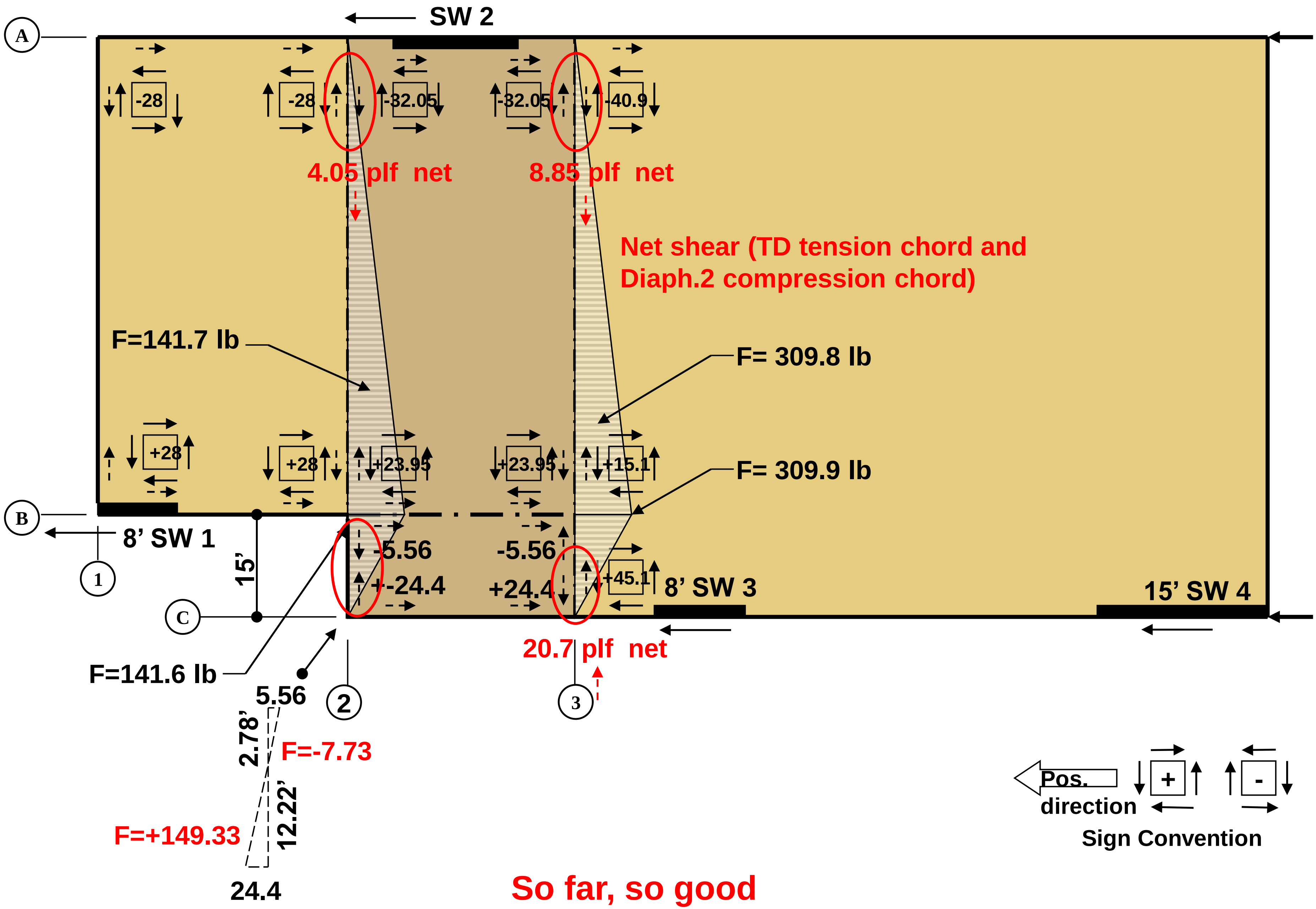
Net Diaphragm Shears

Legend

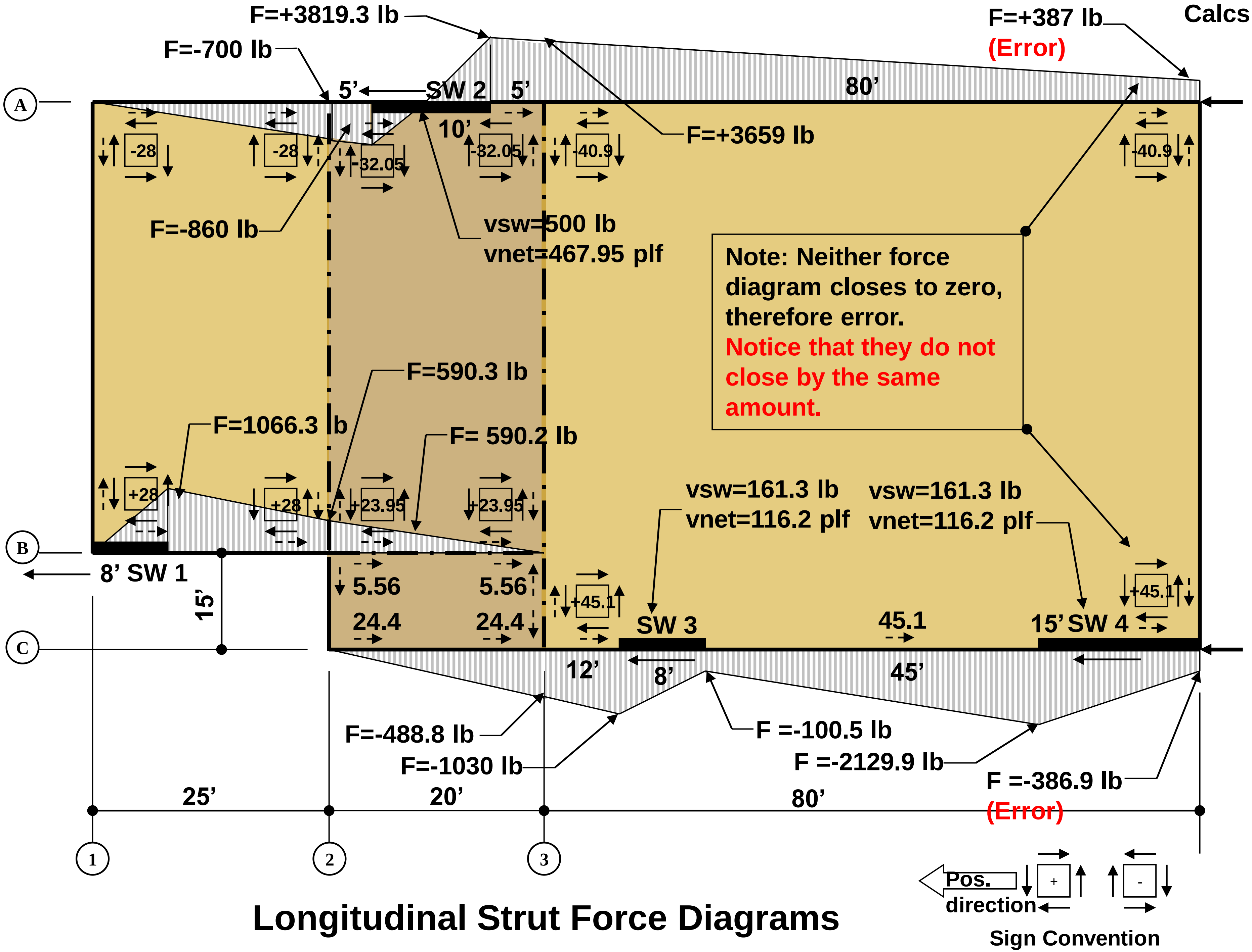
375 plf Basic diaphragm shear

=xxx plf Net diaphragm shears (basic shear +/- TD Shears)

(240 plf) Transfer diaphragm shears

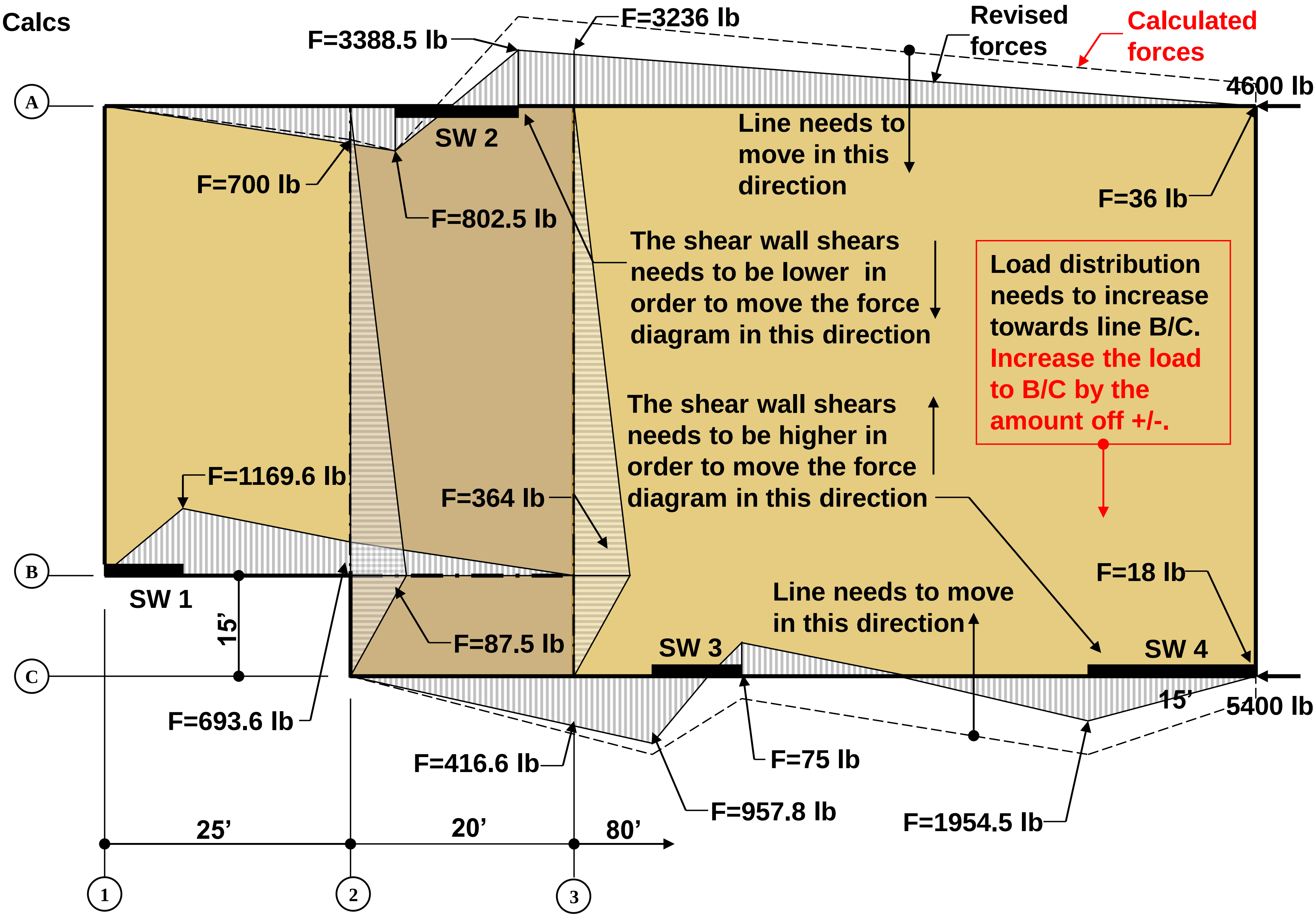


Transverse Collector Force Diagrams



Longitudinal Strut Force Diagrams

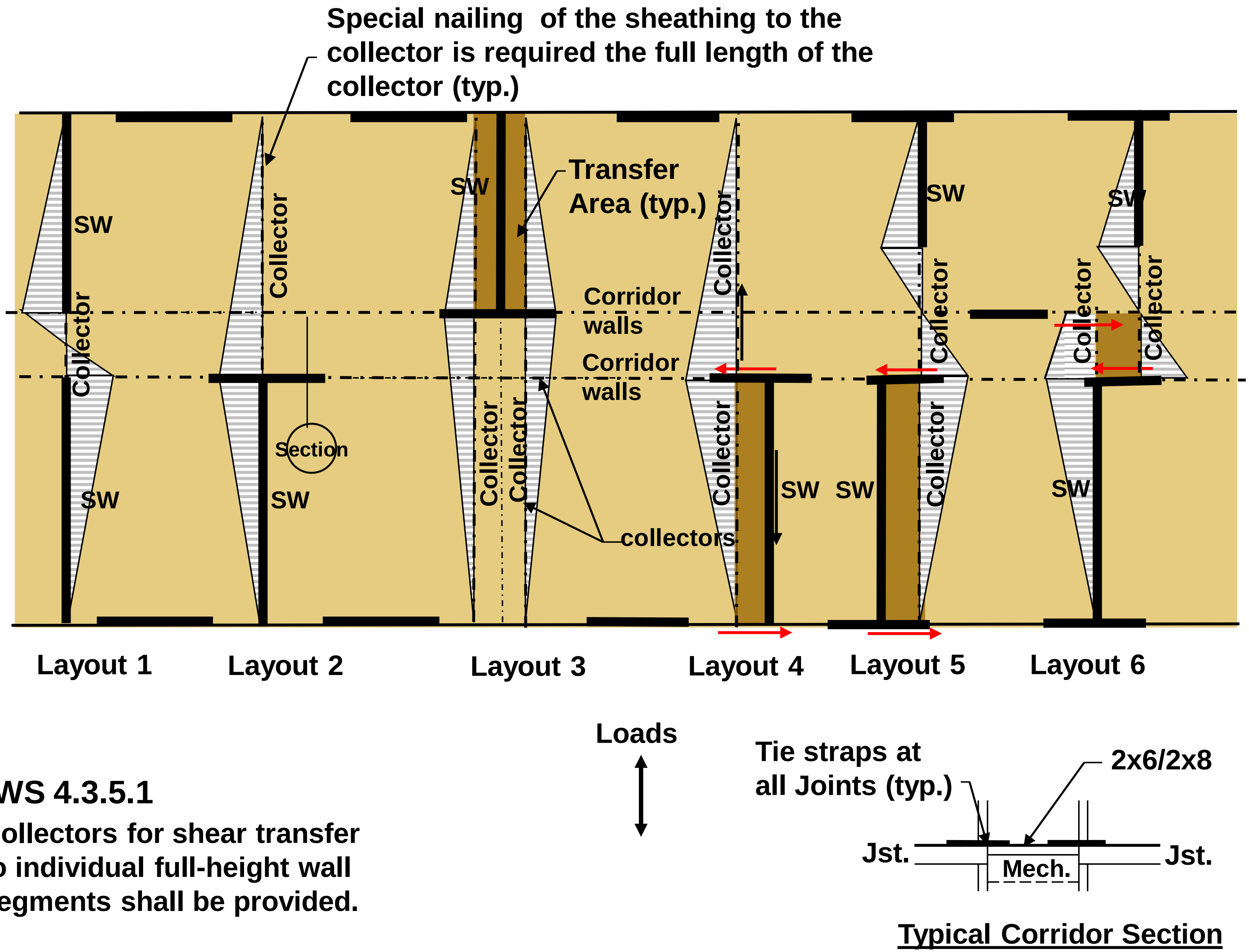
Calcs



Adjusted Longitudinal Strut Force Diagrams (8% increase to B/C)

[Amount shifted to B/C depends on the offset to span ratio of the transfer diaphragm]

Tying Shear Walls Across the Corridor ??

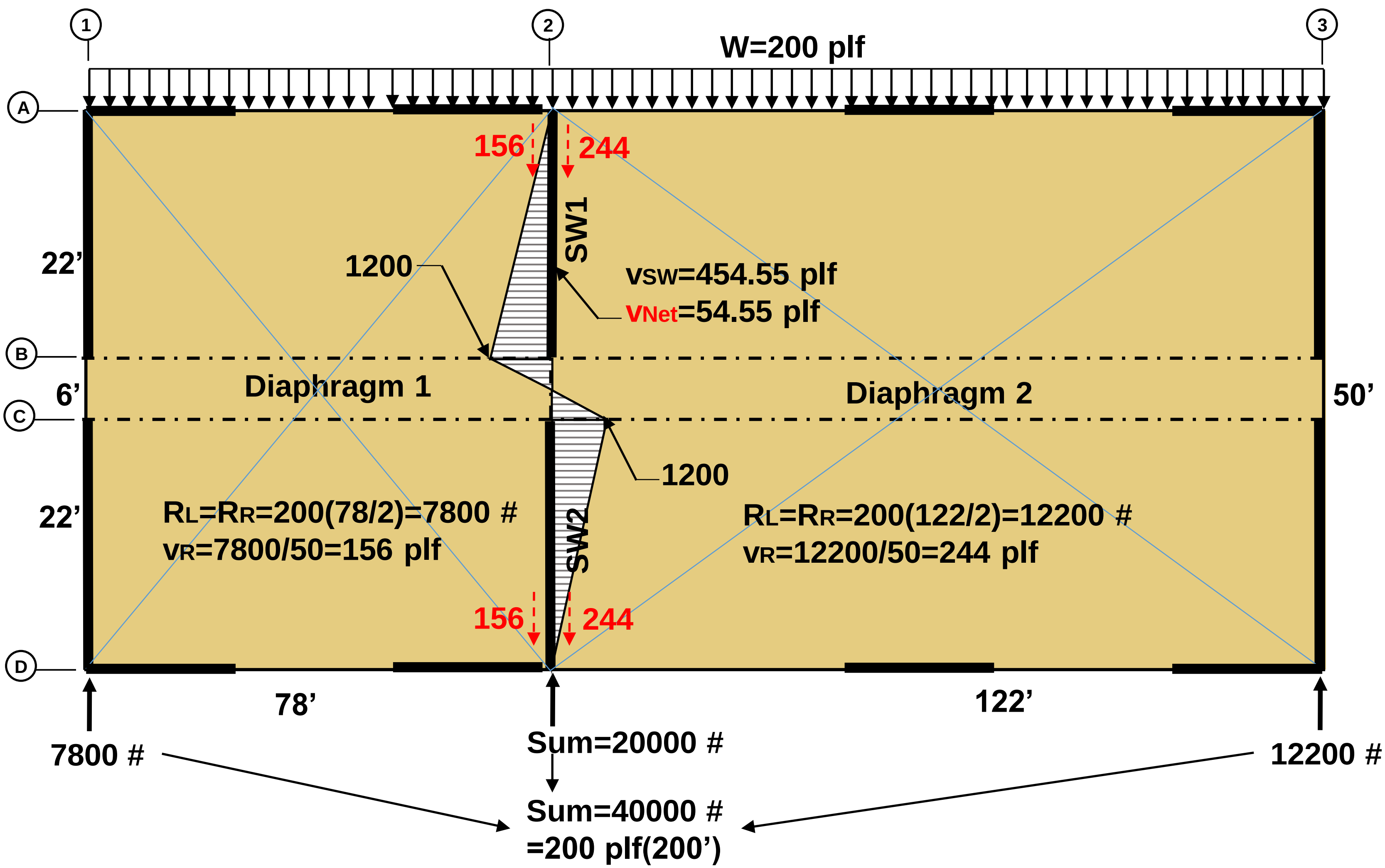


SDPWS 4.3.5.1

3. Collectors for shear transfer to individual full-height wall segments shall be provided.

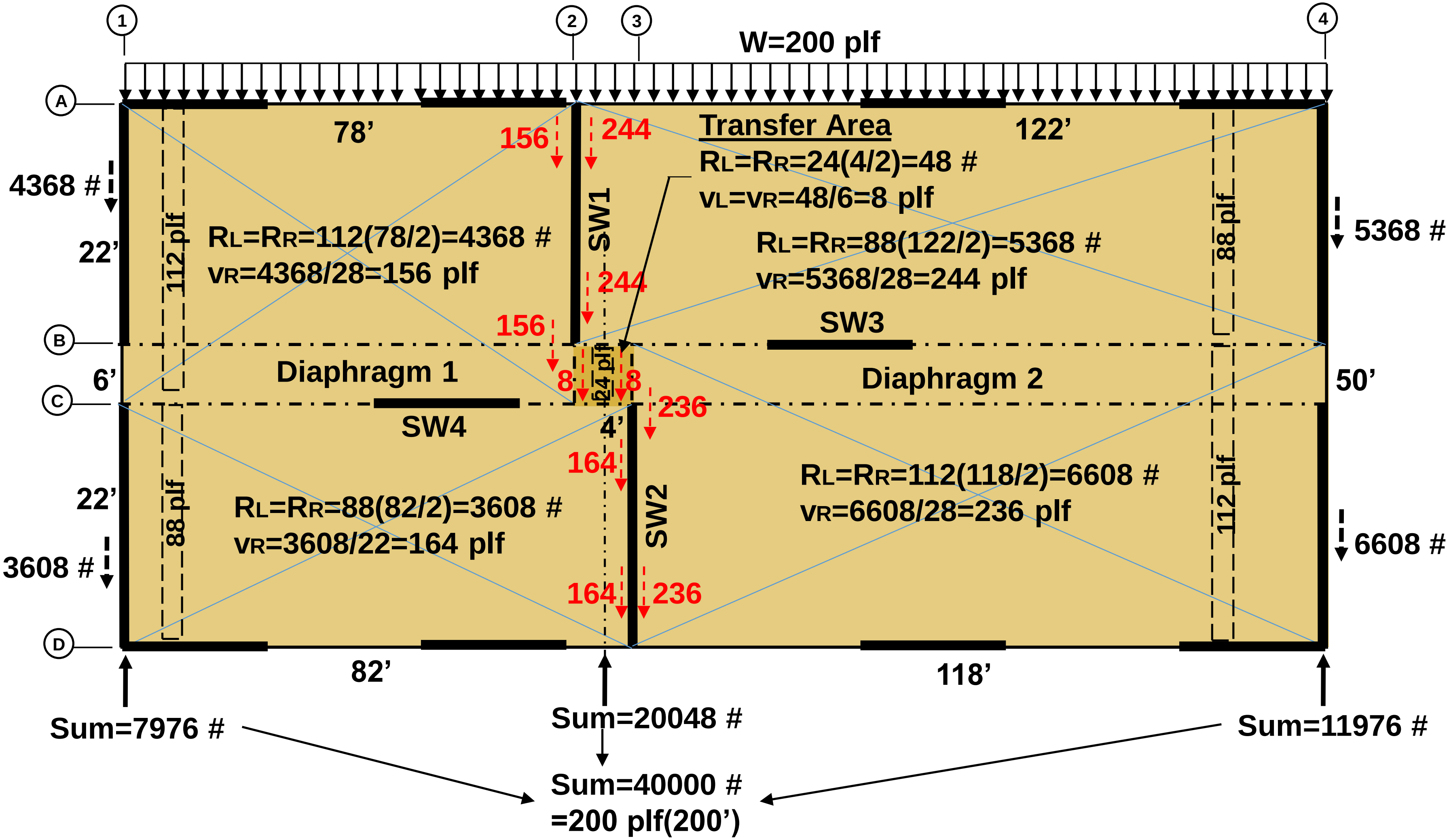
Common Transverse Wall Layouts

Layout 1-Full length walls aligned

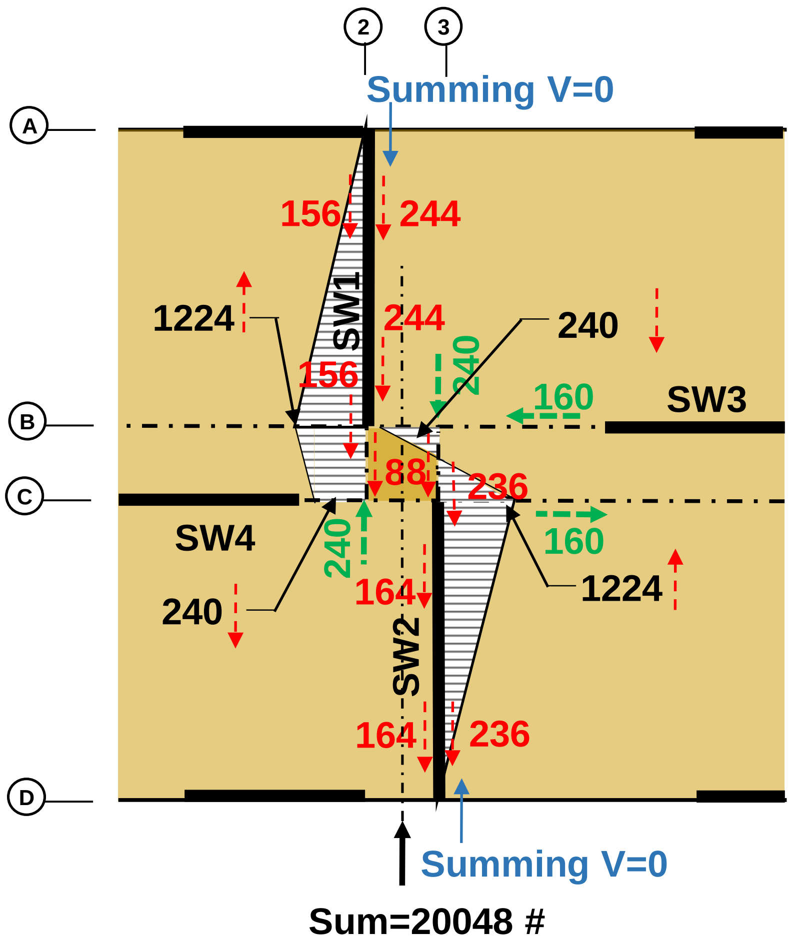


Example 4-Offset Shear Walls Across the Corridor-Layout 6

<u>Layout 6, Case1</u>-Full length offset walls



Case 1-Smaller resulting forces at corridor



All forces in lb., all shears in plf

Total load to grid lines 2 & 3

R_{23}=4368+3608+48+5368+6608+48=20048 # O.K.

L_{SW}=22+22=44'
V_{SW}=20048 #
v_{SW}=20048/44=455.64 plf

v_{net} SW1=455.64-156-244=55.64 plf
v_{net} SW2=455.64-164-236=55.64 plf Checks, they should be equal

SW1
F_{2AB}=55.64(22)=1224 #
F_{2BC}=(156+8)6=984 #
F_{2C}=1224-984=240 #

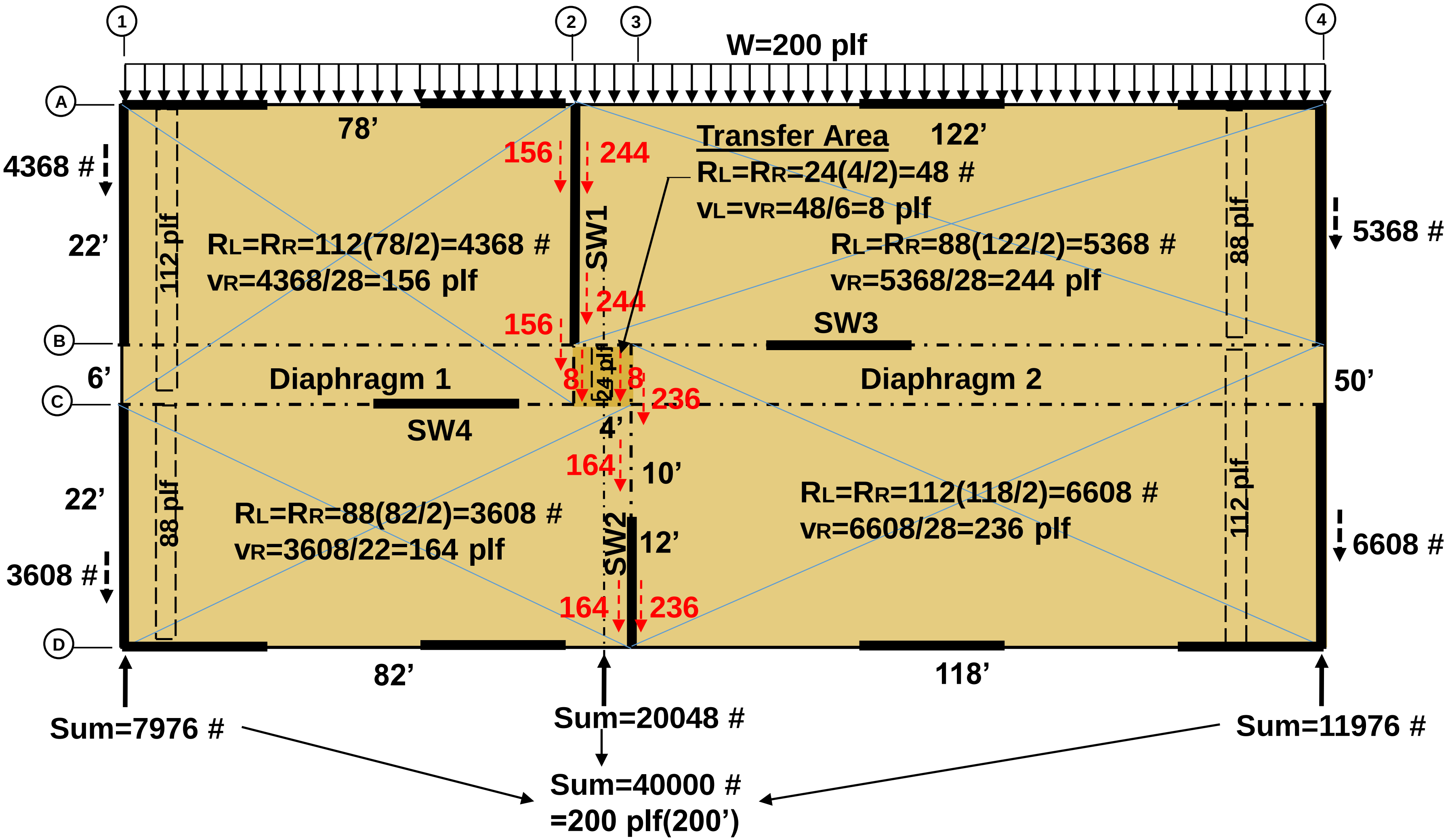
O.K.

SW2
F_{3CD}=55.64(22)=1224 #
F_{3CB}=(236+8)6=1464 #
F_{3B}=1224-1464= -240 #

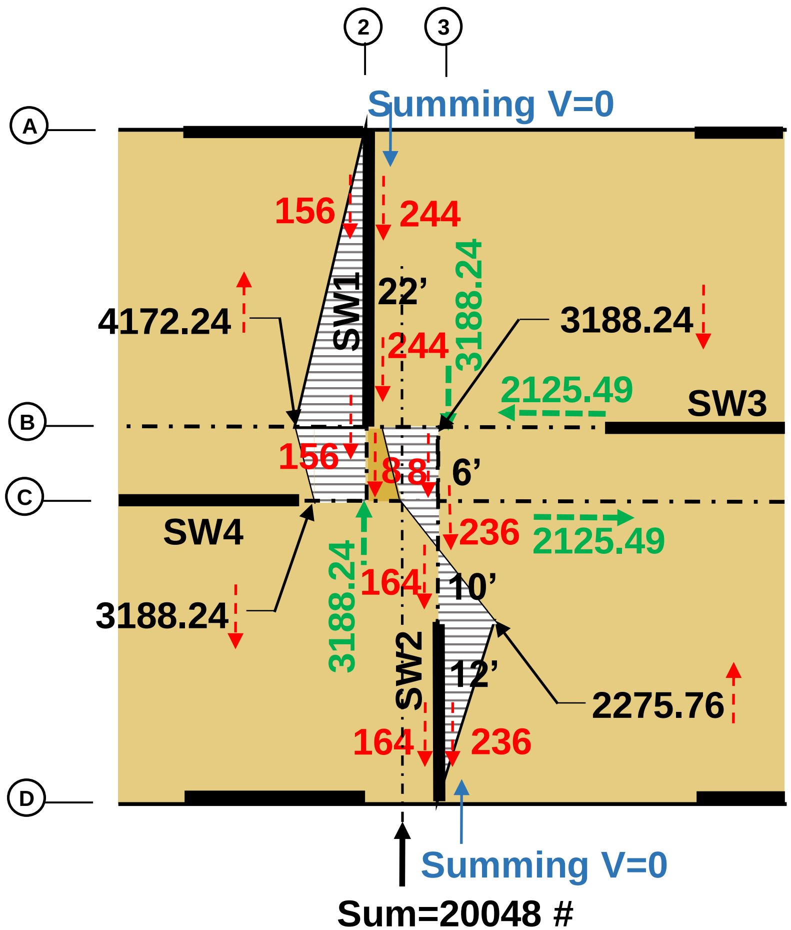
$F_{B23}=F_{C23}$=240(4)/6=160 #

Shear at transfer area=240/6+8=48 plf

Layout 6, Case2-Full length plus partial length offset shear walls



Case 2-Larger resulting forces at corridor



All forces in lb., all shears in plf

Total load to grid lines 2 & 3

R23=4368+3608+48+5368+6608+48=20048 # O.K.

LSW=22+12=34'
VSW=20048 #
vSW=20048/34=589.65 plf

vnet SW1=589.65-156-244=189.65 plf
vnet SW2=589.65-164-236=189.65 plf Checks, they should be equal

SW1

F2AB=189.65(22)=4172.24 #
F2BC=(156+8)6=984 #
F2C=4172.24-984=3188.24 #

O.K.

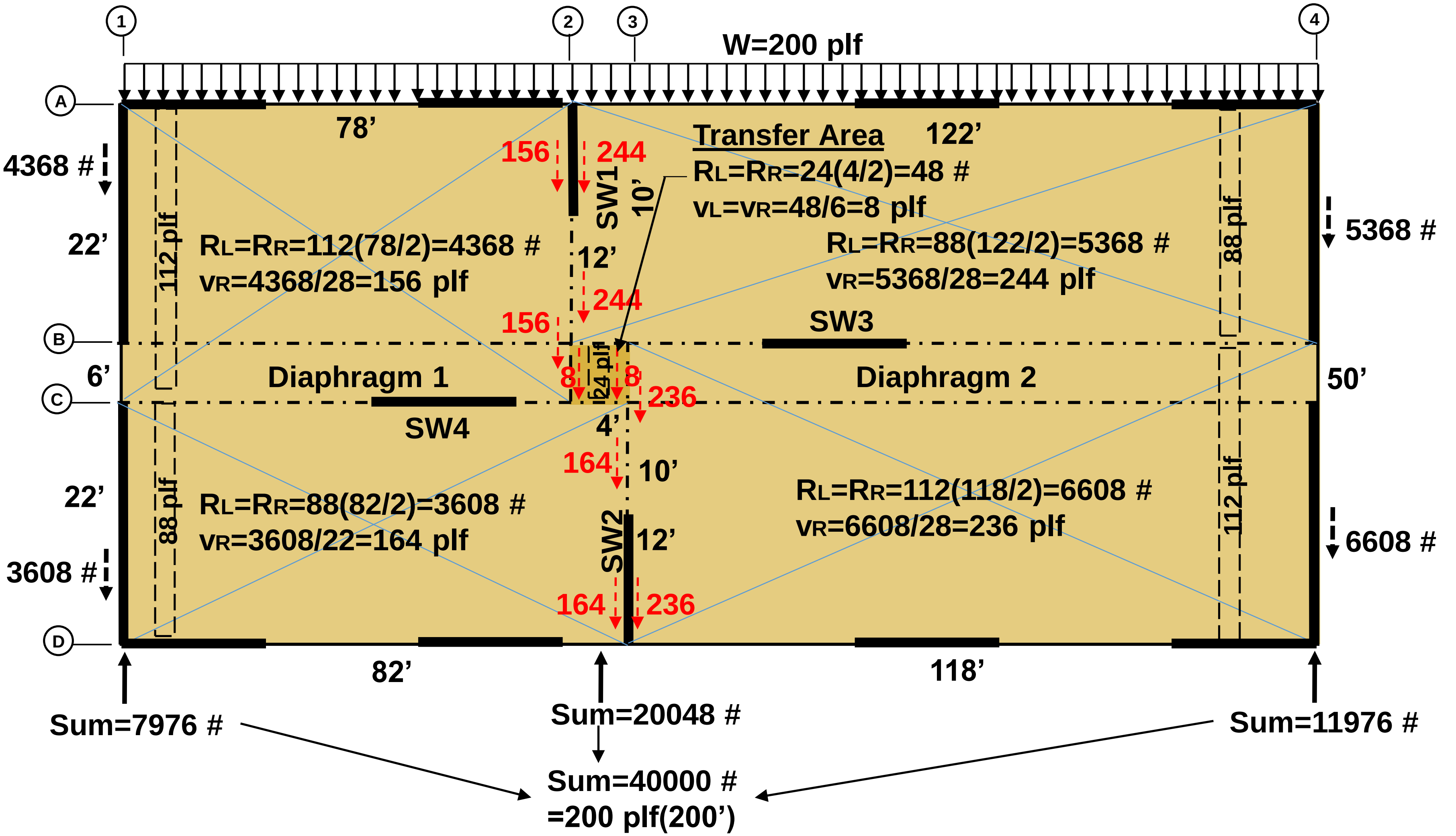
SW2

FSW2 =189.65(12)=2275.76 #
FSW2 to 3B=(236+8)6+(236+164)10=5464 #
F3B=2275.76-5464= -3188.24 #

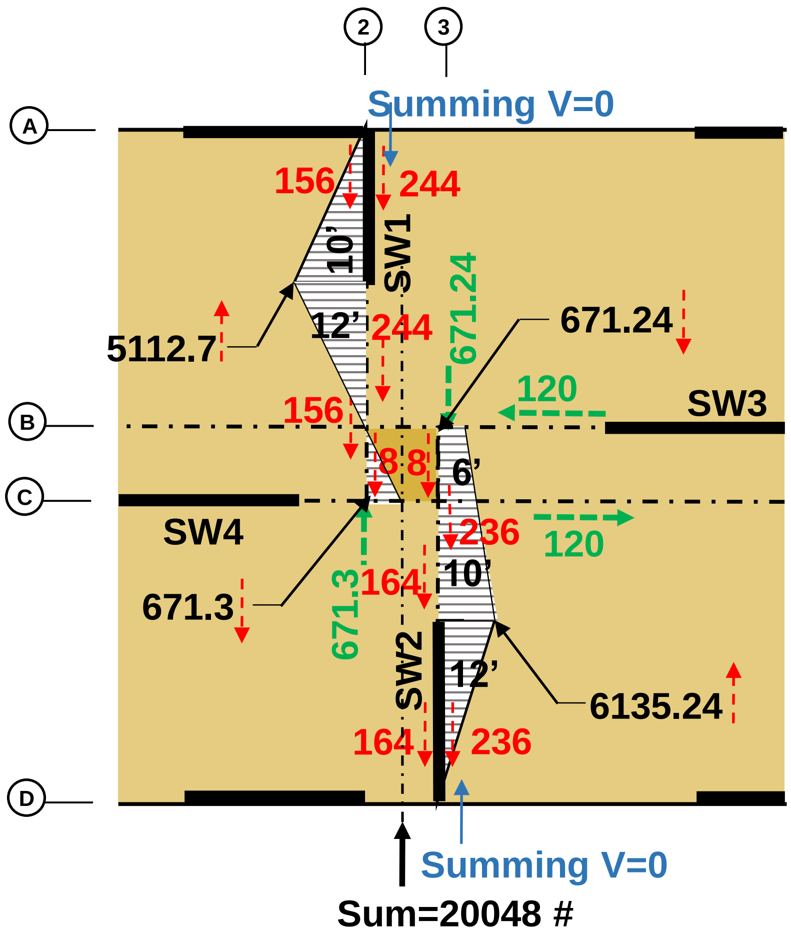
FB23=FC23=3188.24(4)/6=2125.49 #

Shear at transfer area=3188.24/6+8=539.37 plf

Layout 6, Case3 - Partial length offset shear walls



Case 3-Smaller resulting forces at corridor



All forces in lb., all shears in plf

Total load to grid lines 2 & 3

R23=4368+3608+48+5368+6608+48=20048 # O.K.

LSW=12+10=22'
VSW=20048 #
vSW=20048/22=911.27 plf

vnet SW1=911.27-156-244=511.27 plf
vnet SW2=911.27-164-236=511.27 plf Checks, they should be equal

SW1
FSW1=511.27(10)=5112.7 #
FSW1 to 2B=(156+244)12=4800 #
F2BC=(156+8)6=984 #
F2C=5112.7-4800-984=-671.3 #

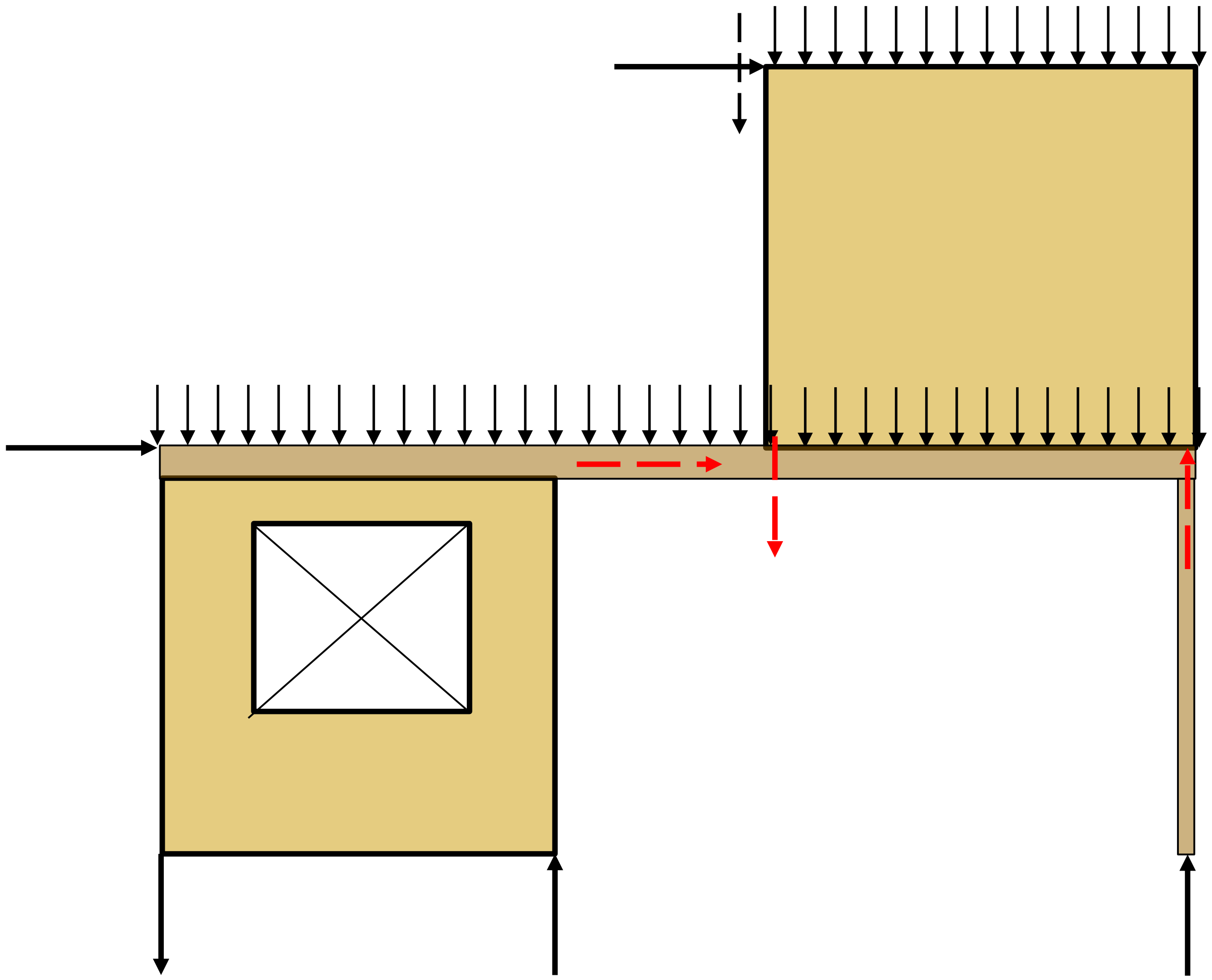
O.K.

SW2
FSW2=511.27(12)=6135.24 #
FSW2 to 3B=(236+8)6+(236+164)10=5464 #
F3B=6135.24-5464= 671.24 #

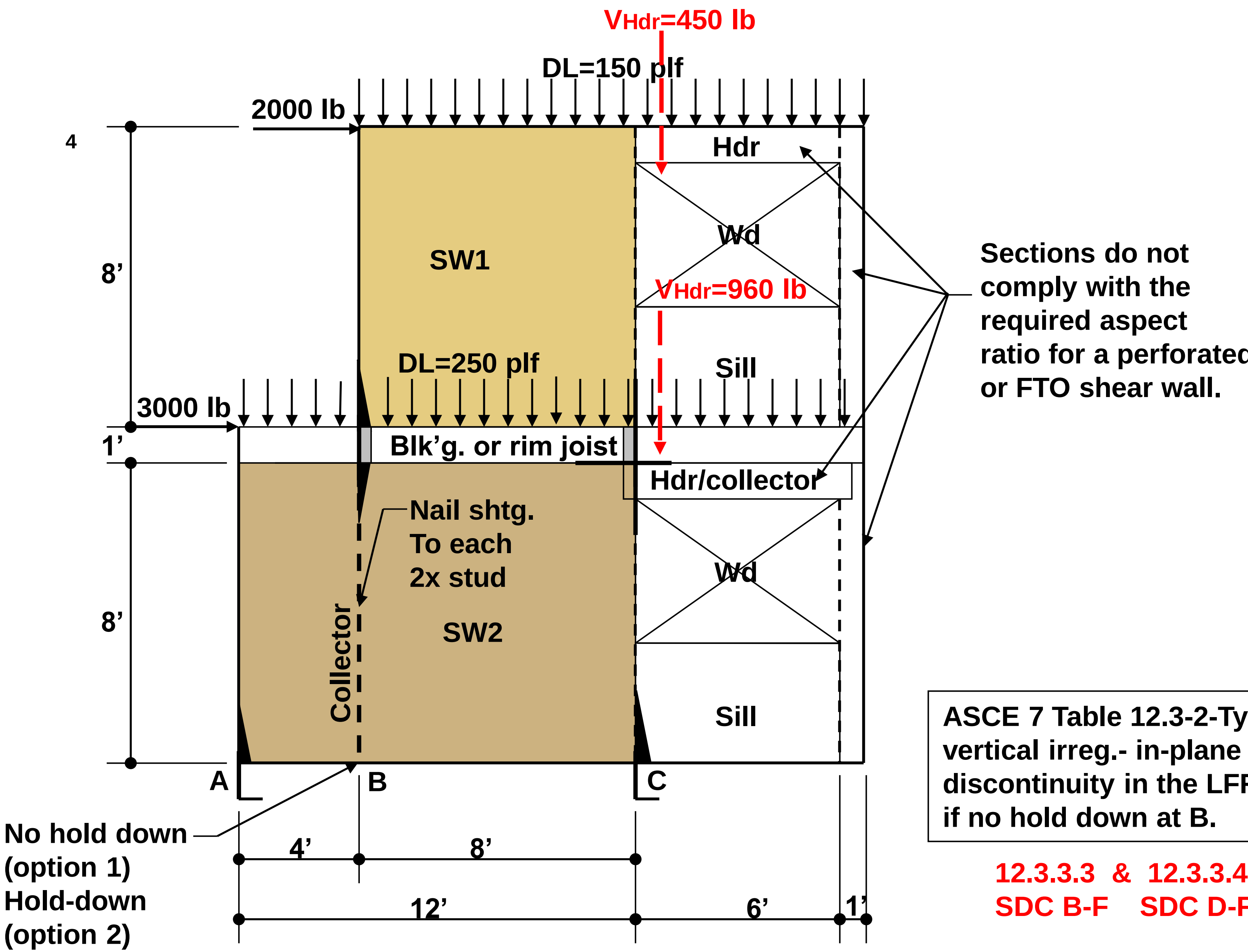
FB23=FC23=671.3(4)/6=120 #

Shear at transfer area=671.3/6+8=119.9 plf

In-plane Offset Shear Walls



Example 5-In-plane Offset Segmented Shear Wall -with Gravity Loads



ASCE 7 Table 12.3-2-Type 4 vertical irreg.- in-plane discontinuity in the LFRS if no hold down at B.

12.3.3.3 & 12.3.3.4
SDC B-F SDC D-F

Ends of wall panels do not line up. Requires special nailing of sheathing into stud below.

Requires same number of studs above and below with boundary nailing each stud

Solid blocking required

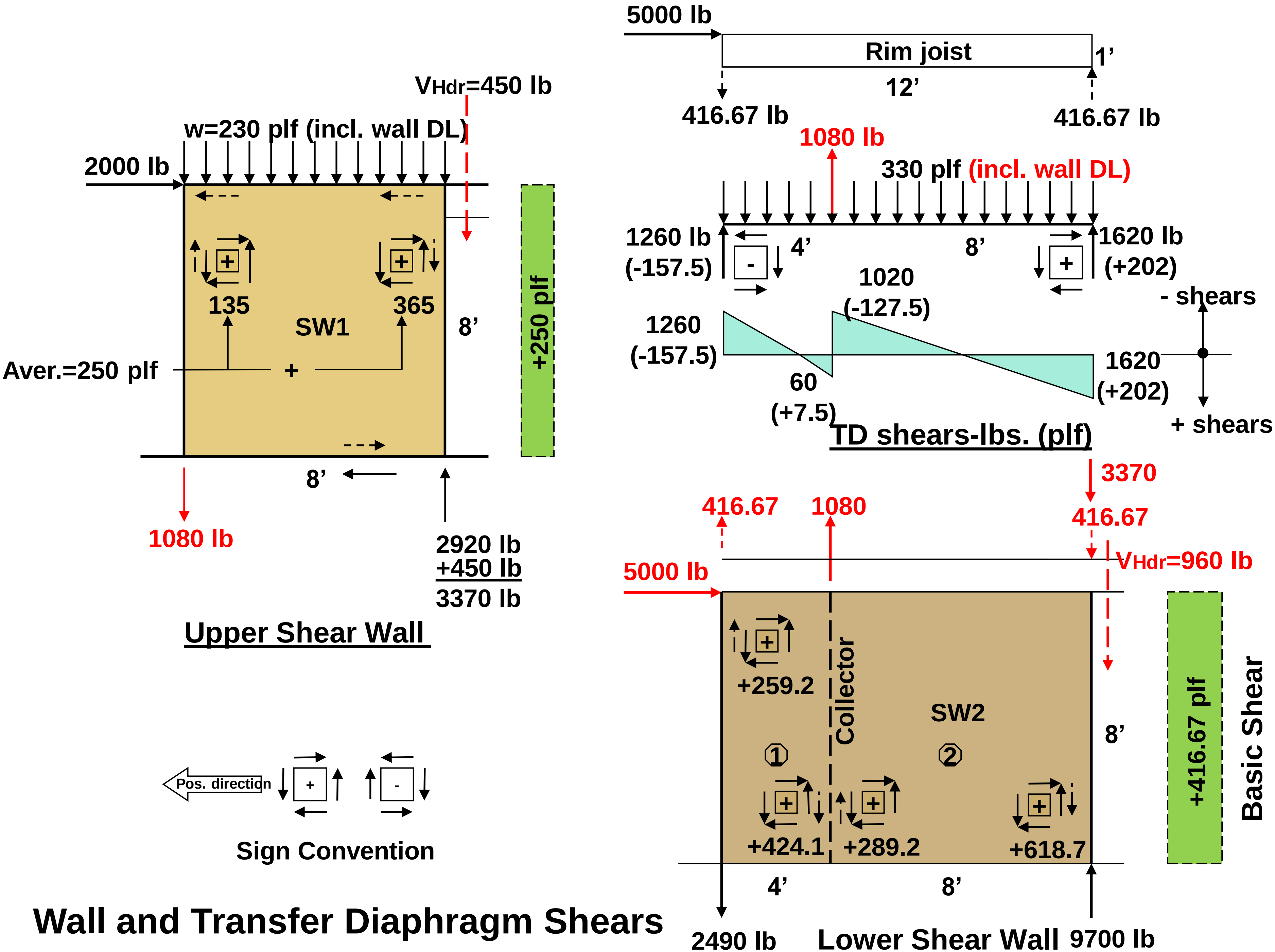
Hold down

Nailing found in field was 12" o.c.

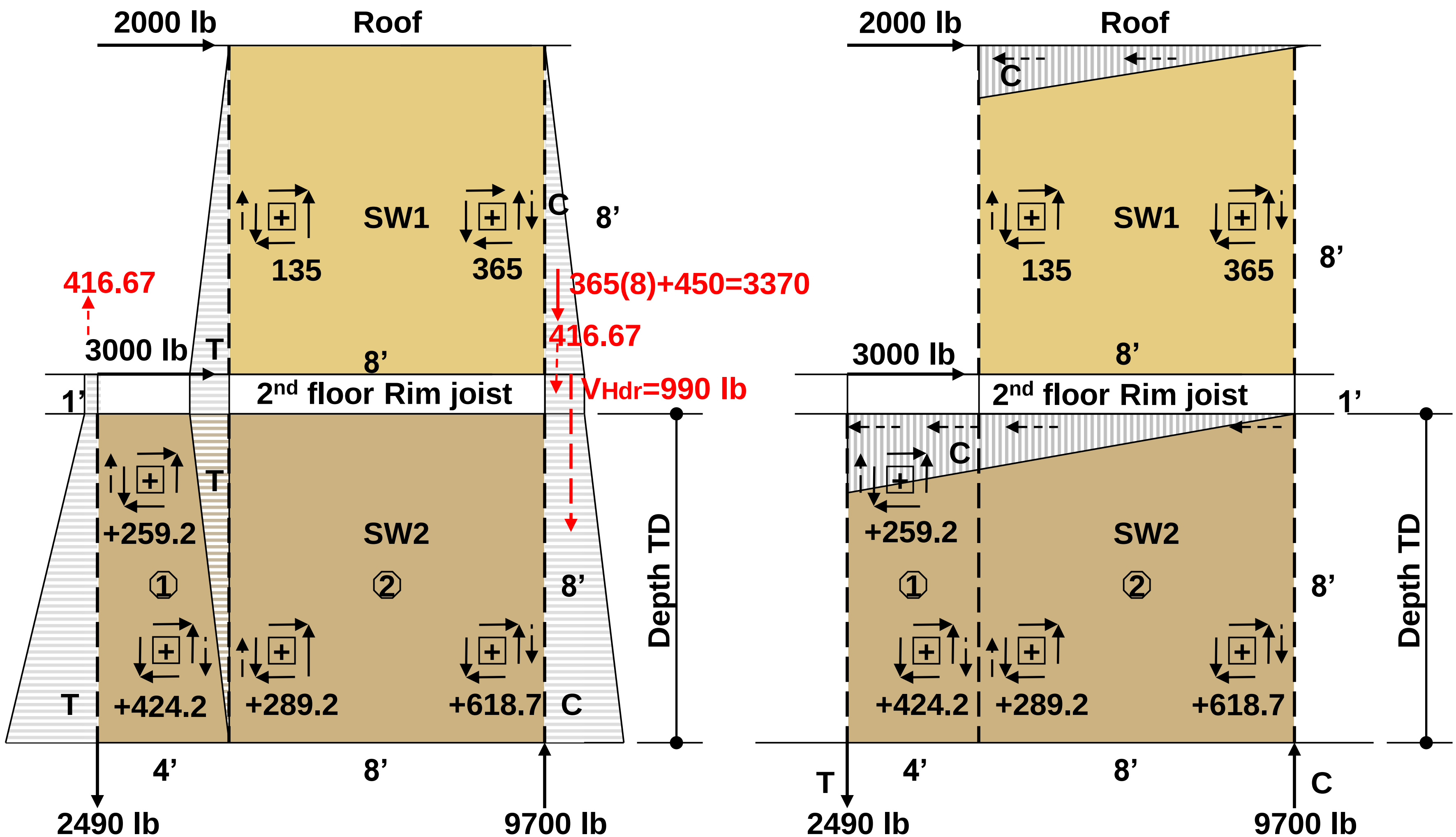
No hold-down below

Hold down

Photo-In-plane Offset Segmented Shear Walls

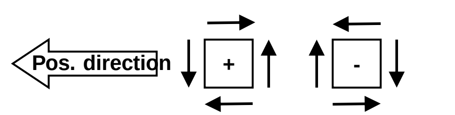


Wall and Transfer Diaphragm Shears



Vertical Collector Forces

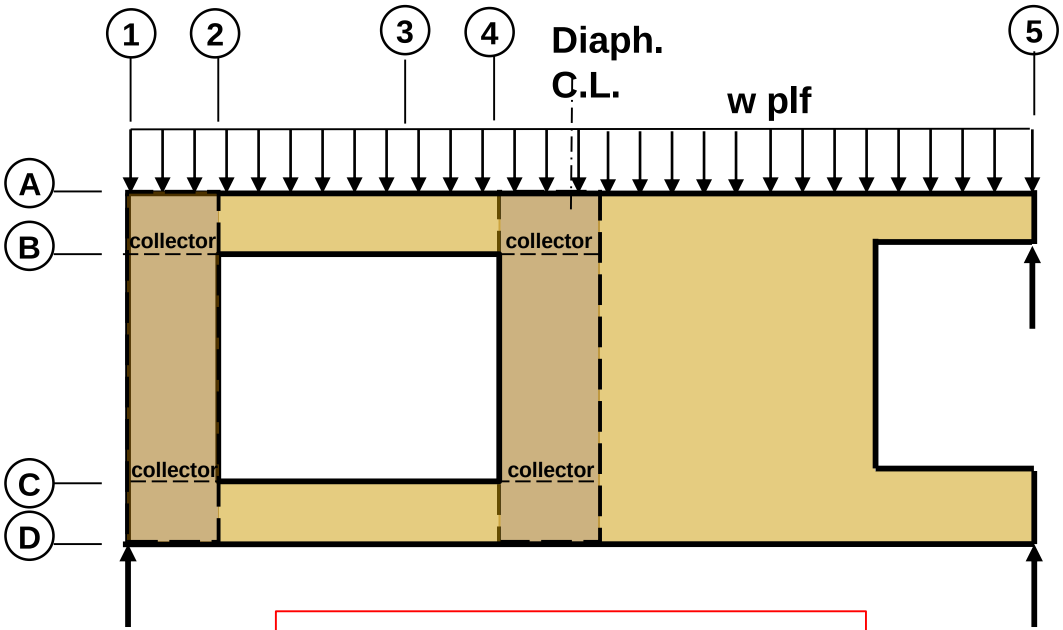
Horizontal Collector Forces



Sign Convention

Collector Force Diagrams

Diaphragms With Large Openings
Interior and End Openings



Diaphragm shears are not required to be increased 25%.

ASCE 7-10 Section 12.3.3.4 (SDC D-F) - Horizontal irregularity Type 3 requires a 25% increase in the diaphragm design forces determined from 12.10.1.1 (Fpx) for the following elements:

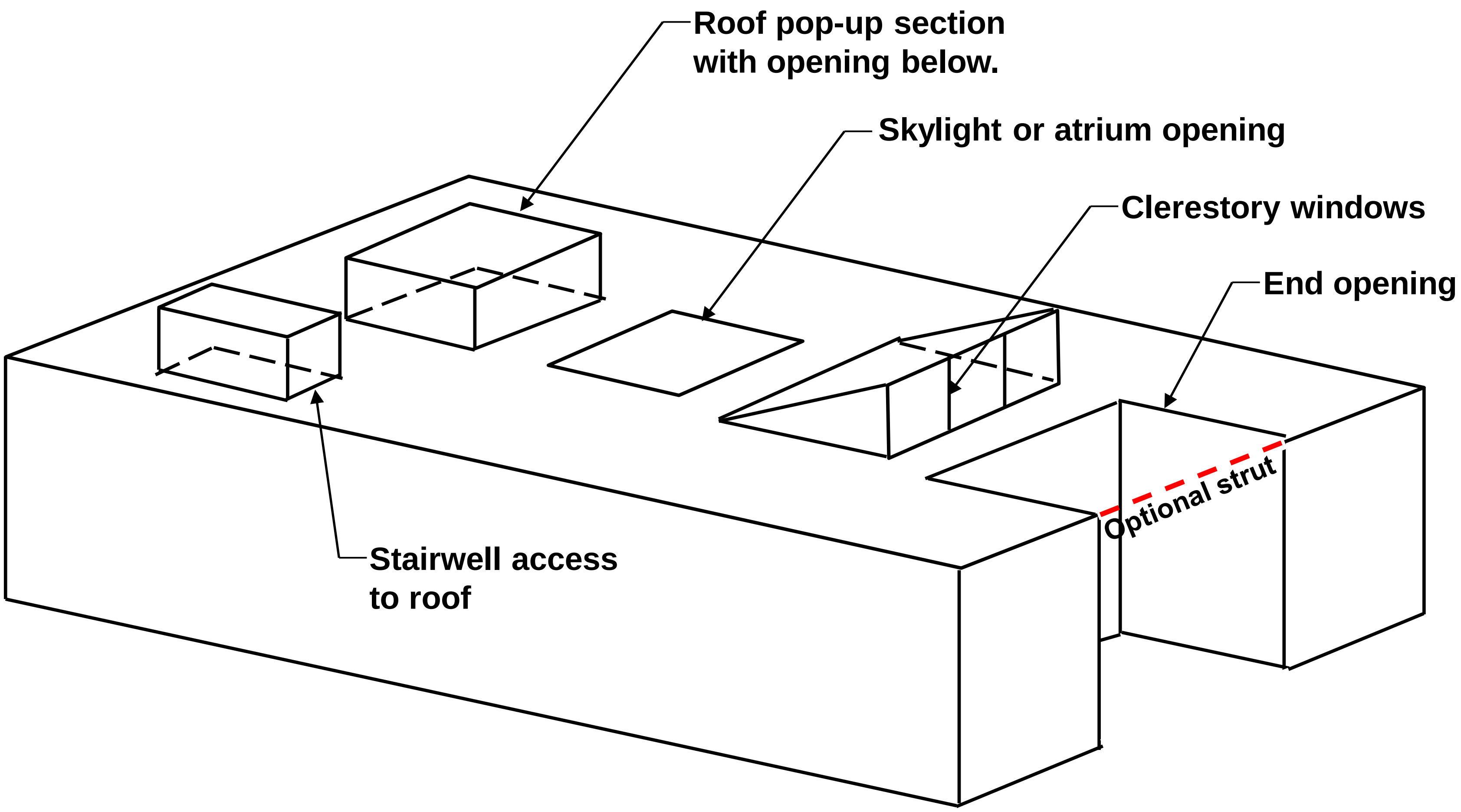
- Connections of diaphragm to vertical elements and collectors (diaphragm supporting elements).

  Collectors and their connections to vertical elements.

  Exception: Forces using the seismic load effects including the over-strength factor of Section 12.4.3 need not be increased.

- Use of over-strength forces is not commonly considered to be triggered for boundary elements at diaphragm openings. However, the 25% increase does apply.

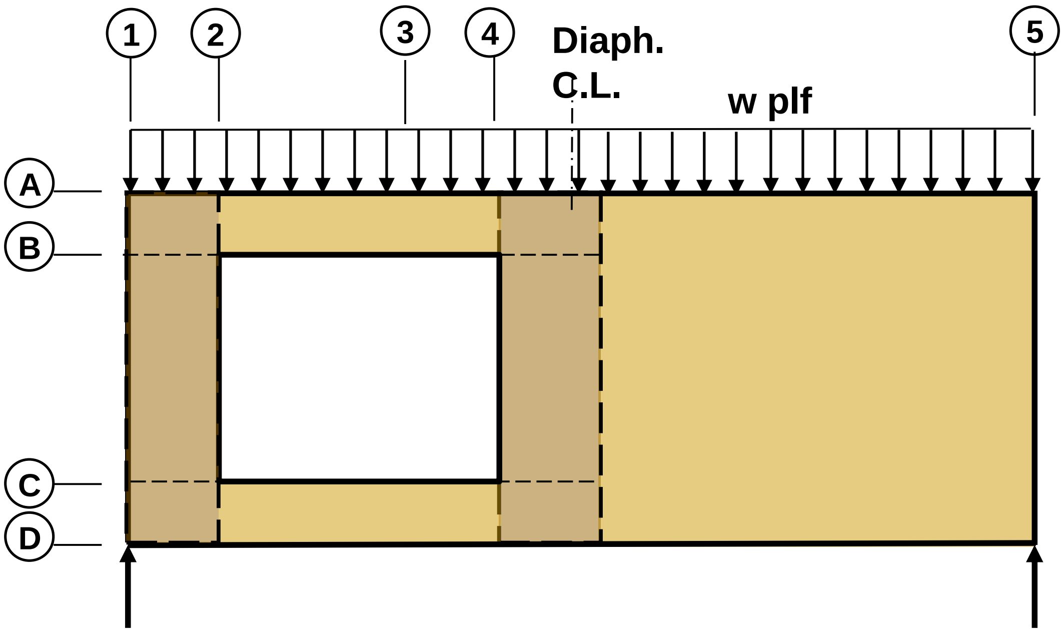
Type 3 Horizontal Irregularity-SDC D-F-Diaphragm Discontinuity Irregularity.
Diaphragm discontinuity irregularity exists where there is an abrupt discontinuity or variation in stiffness, including a cut-out or open area greater than 50% gross enclosed diaphragm area, or a change in effective diaphragm stiffness of more than 50% from one story to the next.



Common Openings In Diaphragms

<u>Harrington Recovery Center</u>
Structural engineer: Pujara Wirth Torke, Inc.
Photographer: Curtis Walz

Interior Openings



IBC 2305.1.1

Openings in shear panels that materially effect their strength shall be fully detailed on the plans and shall have their edges adequately reinforced to transfer all shear stresses.

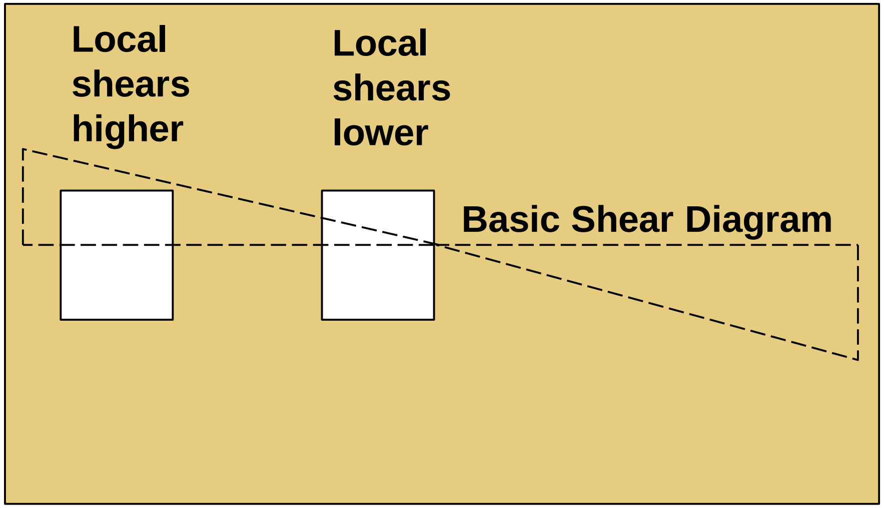
FPInnovations

Design example: Designing for openings in wood diaphragm

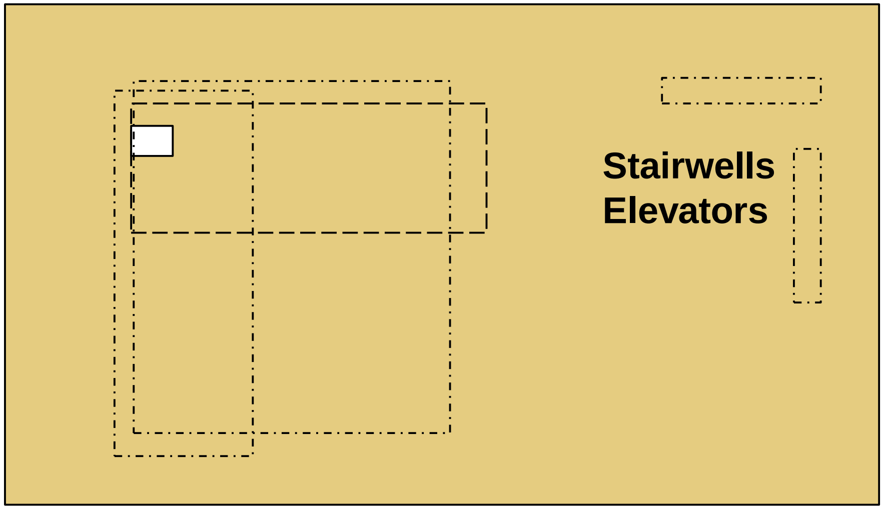
It is strongly recommended that analysis for a diaphragm with an opening should be carried out except where all four of the following items are satisfied:

a. Depth no greater than 15% of diaphragm depth;
b. Length no greater than 15% of diaphragm length;
c. Distance from diaphragm edge to the nearest opening edge is a minimum of 3 times the larger opening dimension;
d. The diaphragm portion between opening and diaphragm edge satisfies the maximum aspect ratio requirement. (all sides of the opening)

Most openings of any significant size should be checked.



Location and Magnitude of Shear

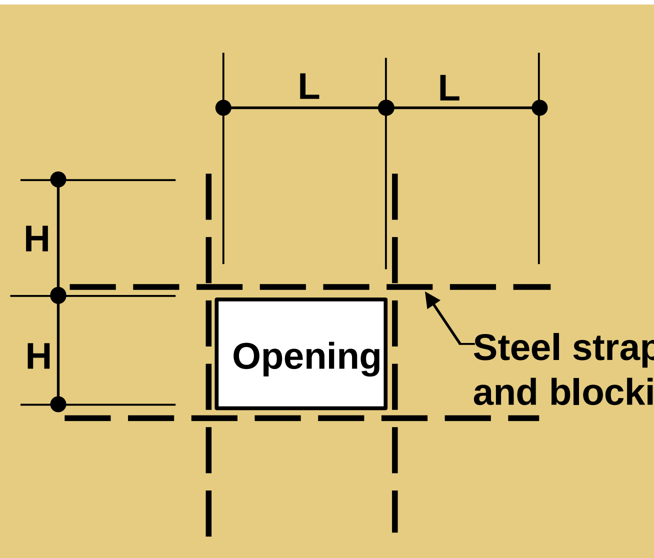


Size of opening

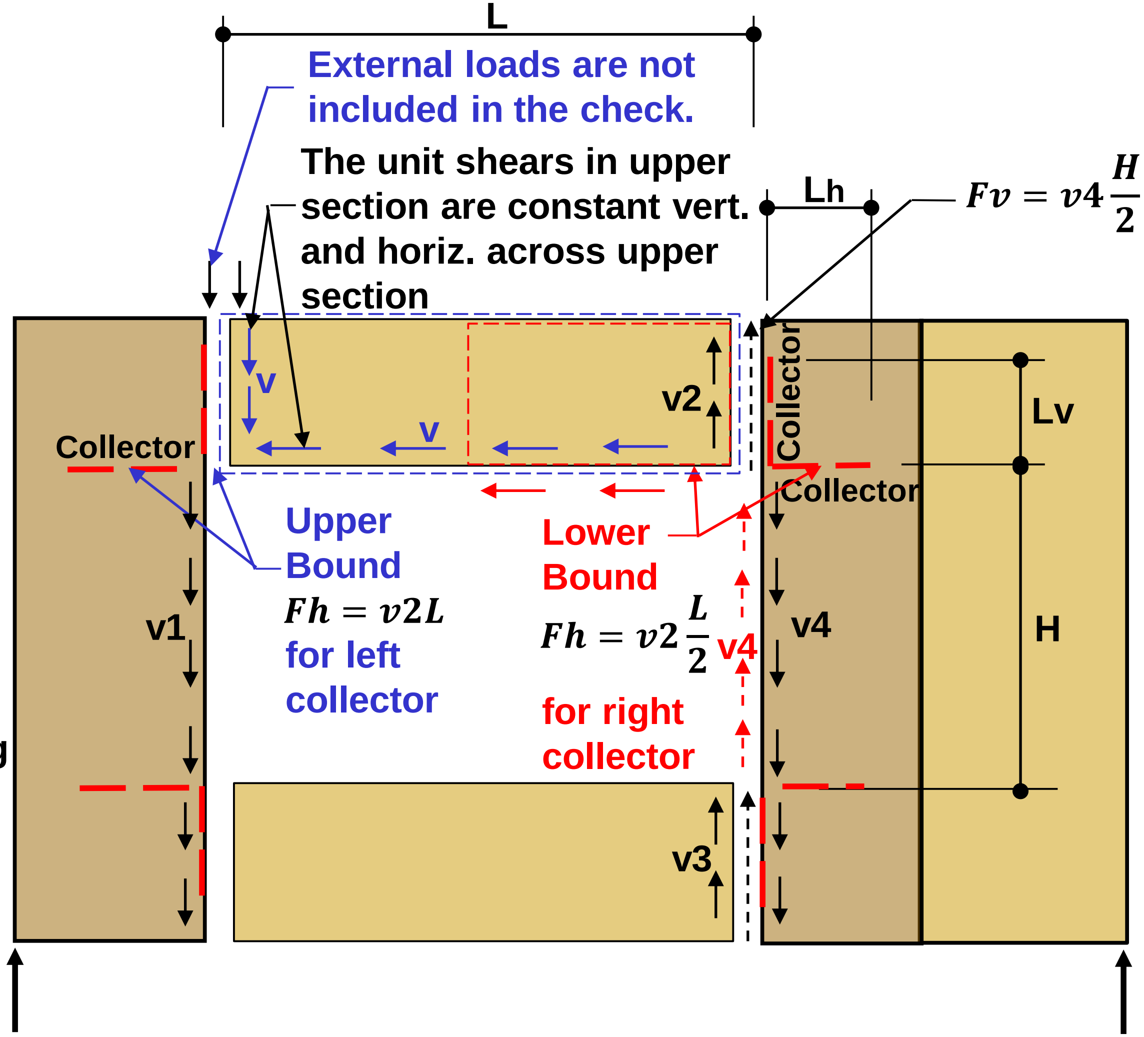
Affect of Size and location in Diaphragm

Opening size is not a factor if:

1. Calculated strap length does not exceed L or H
2. Shear does not increase beyond nailing capacity



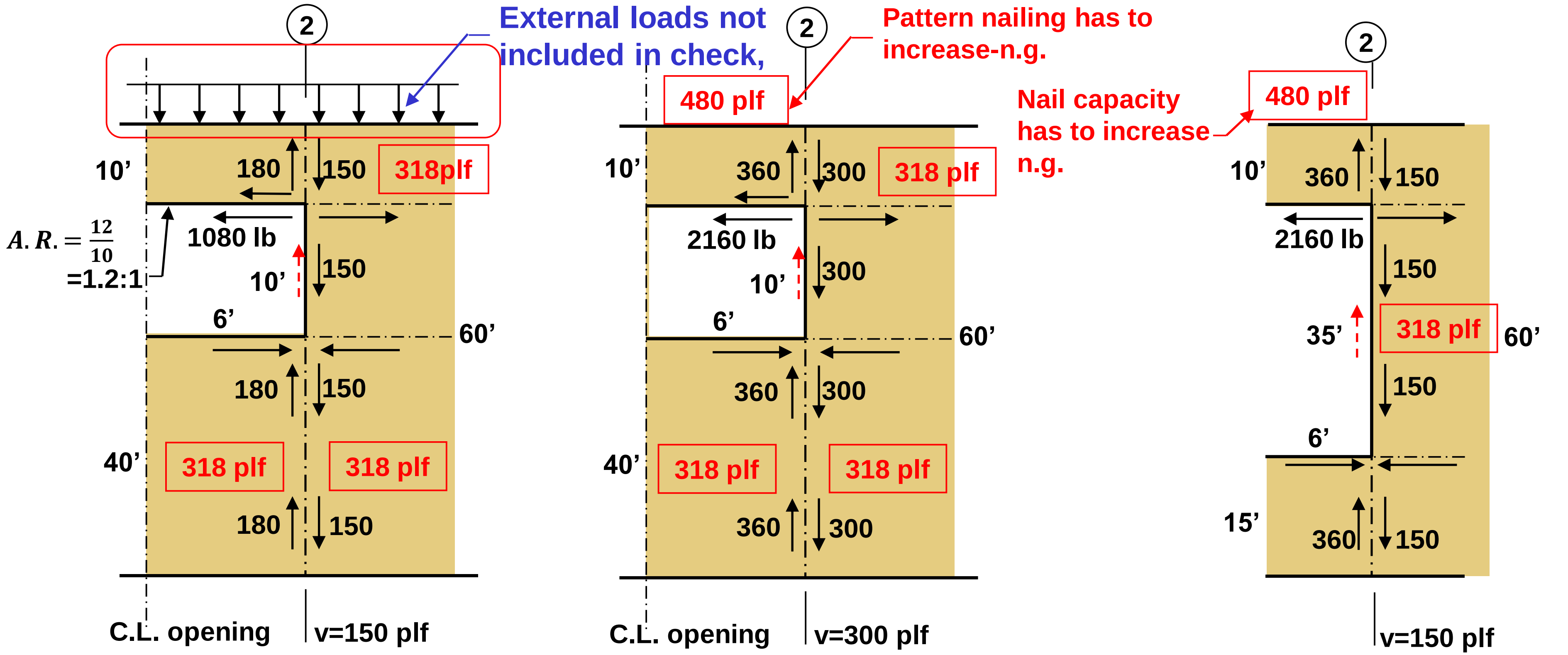
IBC/Diekmann



Minimum recommended steel strap lengths if opening size is not a factor.

1. 2015 IBC Section 2308.4.4.1: If opening > 4 ft. use Figure 2308.4.4.1(1)
   - 16 ga. X 1 ½” x L or H strap w/ (16)16d or engineered
2. Diekmann, ATC-7: Rule of thumb as shown above.

Diekmann Method Of Checking If Opening Size Is A Factor



12' L x 10' H Opening — Located at low shear

$$F_V = \frac{150(10)}{2} = 750\text{ lb}$$

$$L_V = \frac{750}{(318-180)} = 5.43' < 10'$$ o.k.

$$F_H = 180(6) = 1080\text{ lb}$$ Lower bound

$$L_H = \frac{1080}{(318-150)} = 6.42' < 12'$$ o.k.

Opening <u>is not</u> a factor

<u>12' L x 10' H Opening</u>

Located at low shear

12' L x 10' H Opening — Located at high shear

$$F_V = \frac{300(10)}{2} = 1500\text{ lb}$$

$$L_V = \frac{1500}{(480-360)} = 12.5' > 10'$$ n.g.

$$F_H = 360(6) = 2160\text{ lb}$$ Lower bound

$$L_H = \frac{2160}{(318-300)} = 120' > 12'$$ n.g.

Opening <u>is</u> a factor

<u>12' L x 10' H Opening</u>

Located at high shear

12' L x 35' H Opening — Located at low shear

$$F_V = \frac{150(35)}{2} = 2625\text{ lb}$$

$$L_V = \frac{2625}{(480-360)} = 21.885' < 35'$$ But > depth

$$F_H = 360(6) = 2160\text{ lb}$$ Lower bound

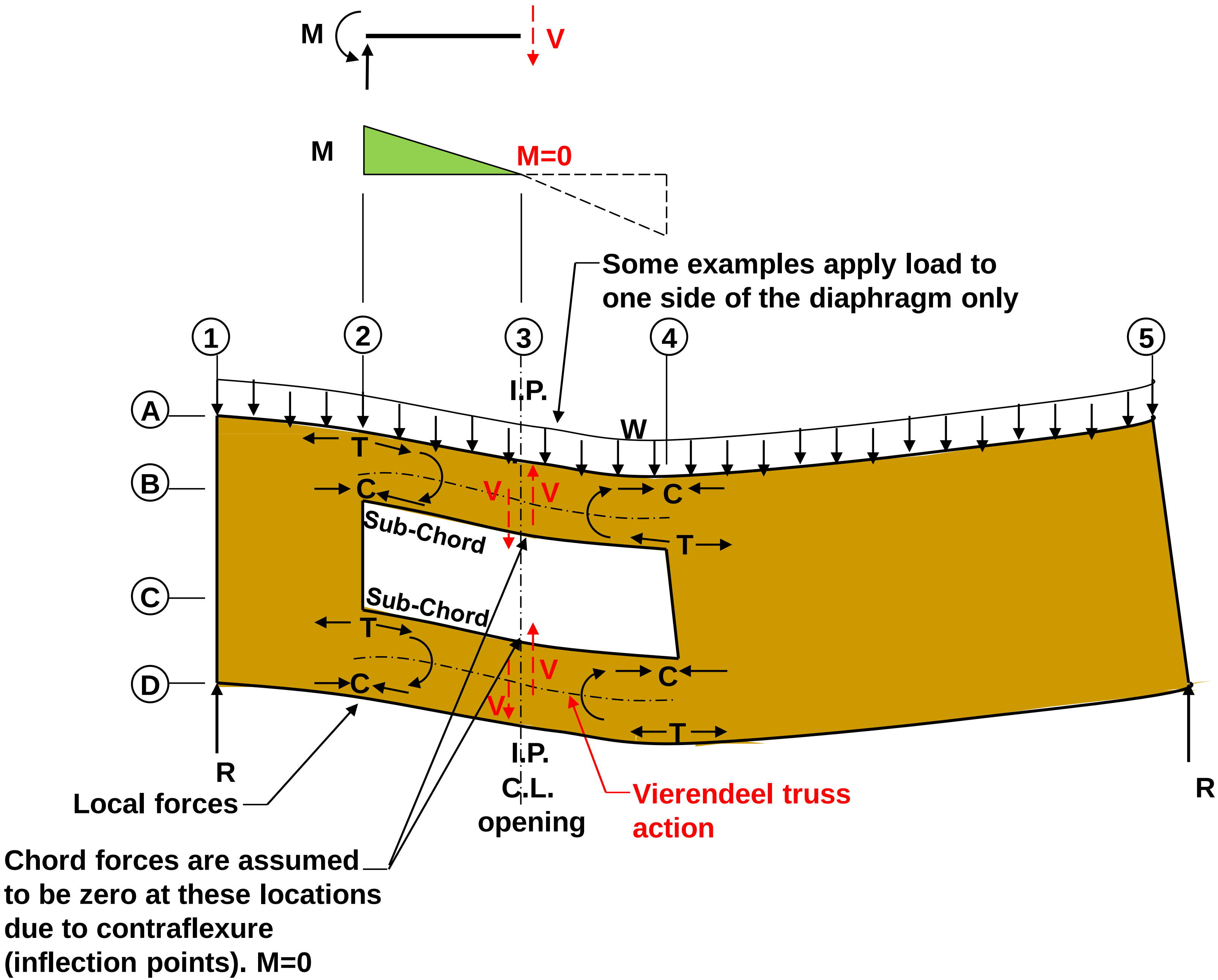
$$L_H = \frac{2160}{(318-150)} = 12.85' > 12'$$ n.g.

Opening <u>is</u> a factor

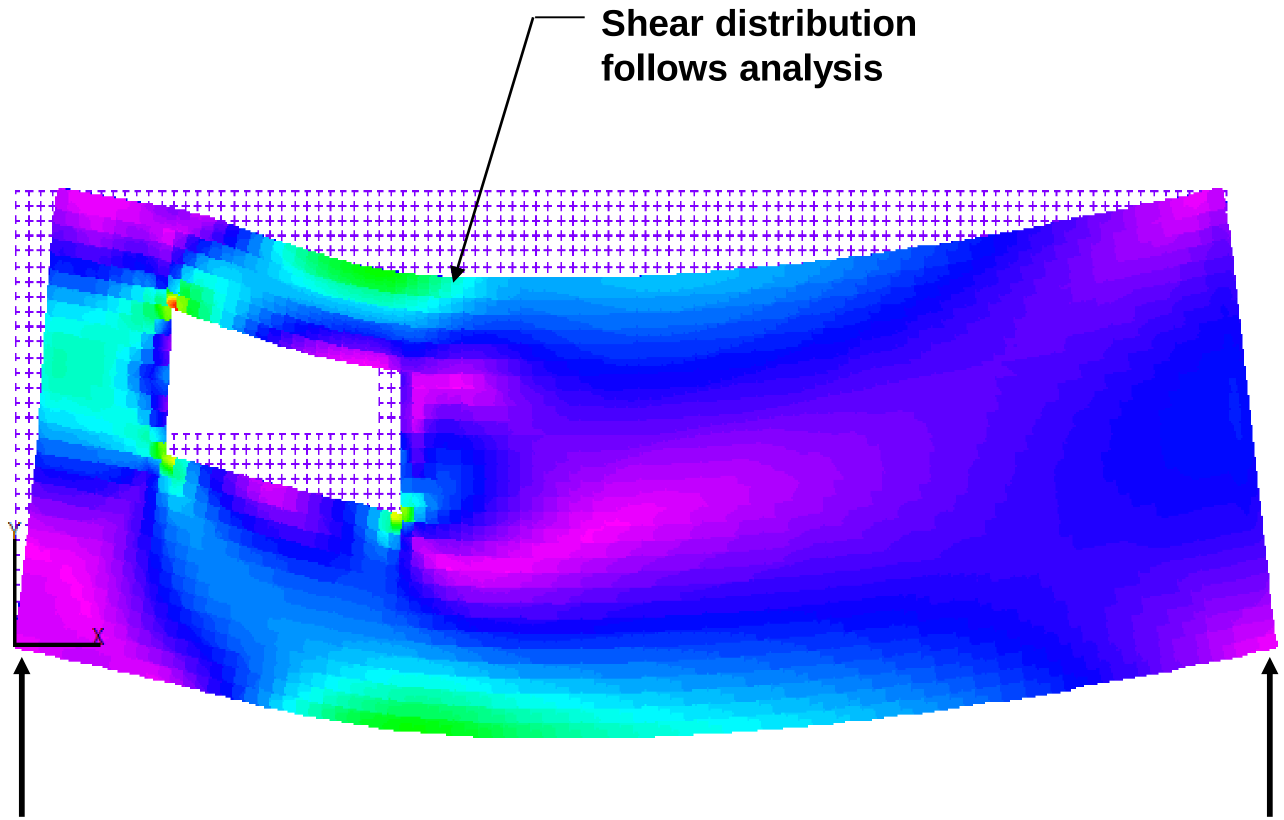
<u>12' L x 35' H Opening</u>

Located at low shear

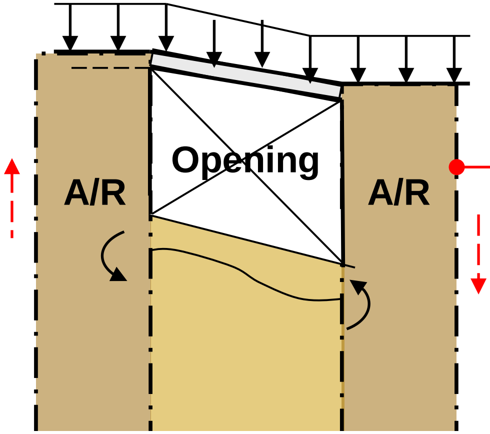
Check If Size and Location of Opening In Diaphragm Is A Factor

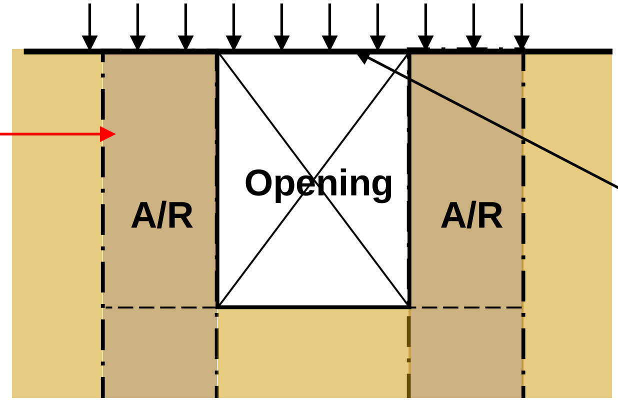


Displacement and Local Forces



Shear Distribution in Diaphragm

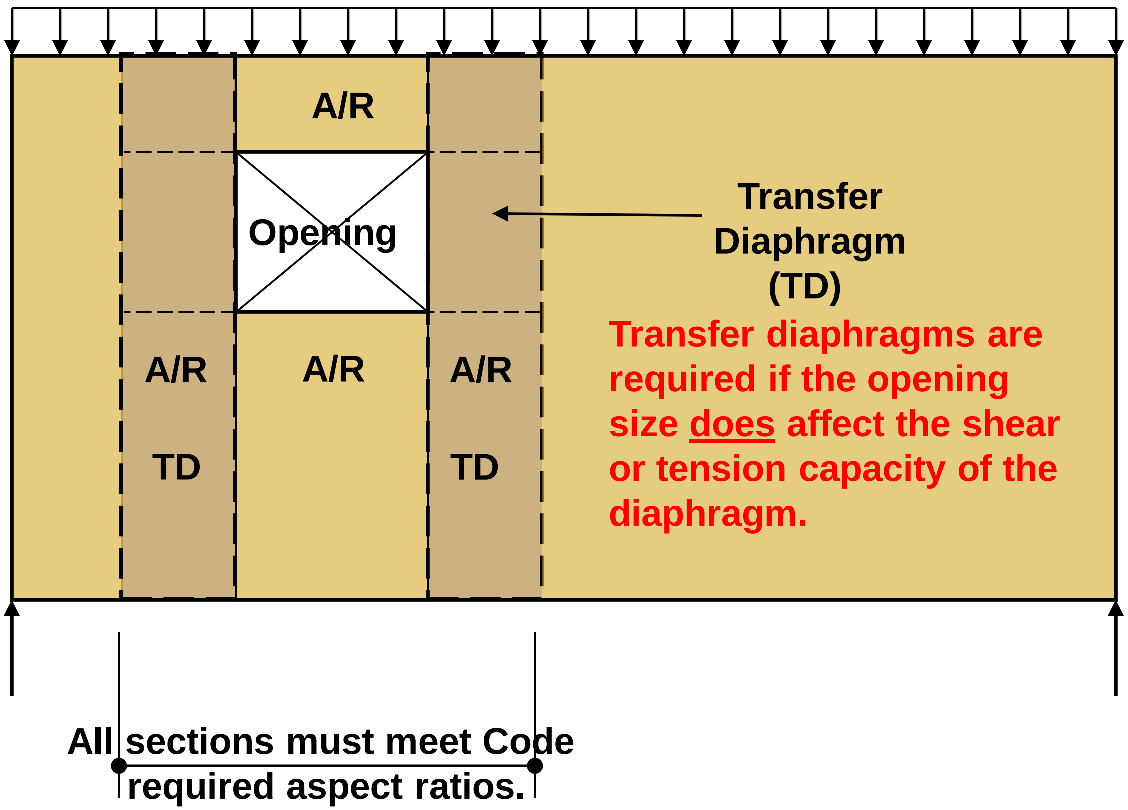




Easy to visualize if header section is replaced by a wire.

Analyze by envelope method:

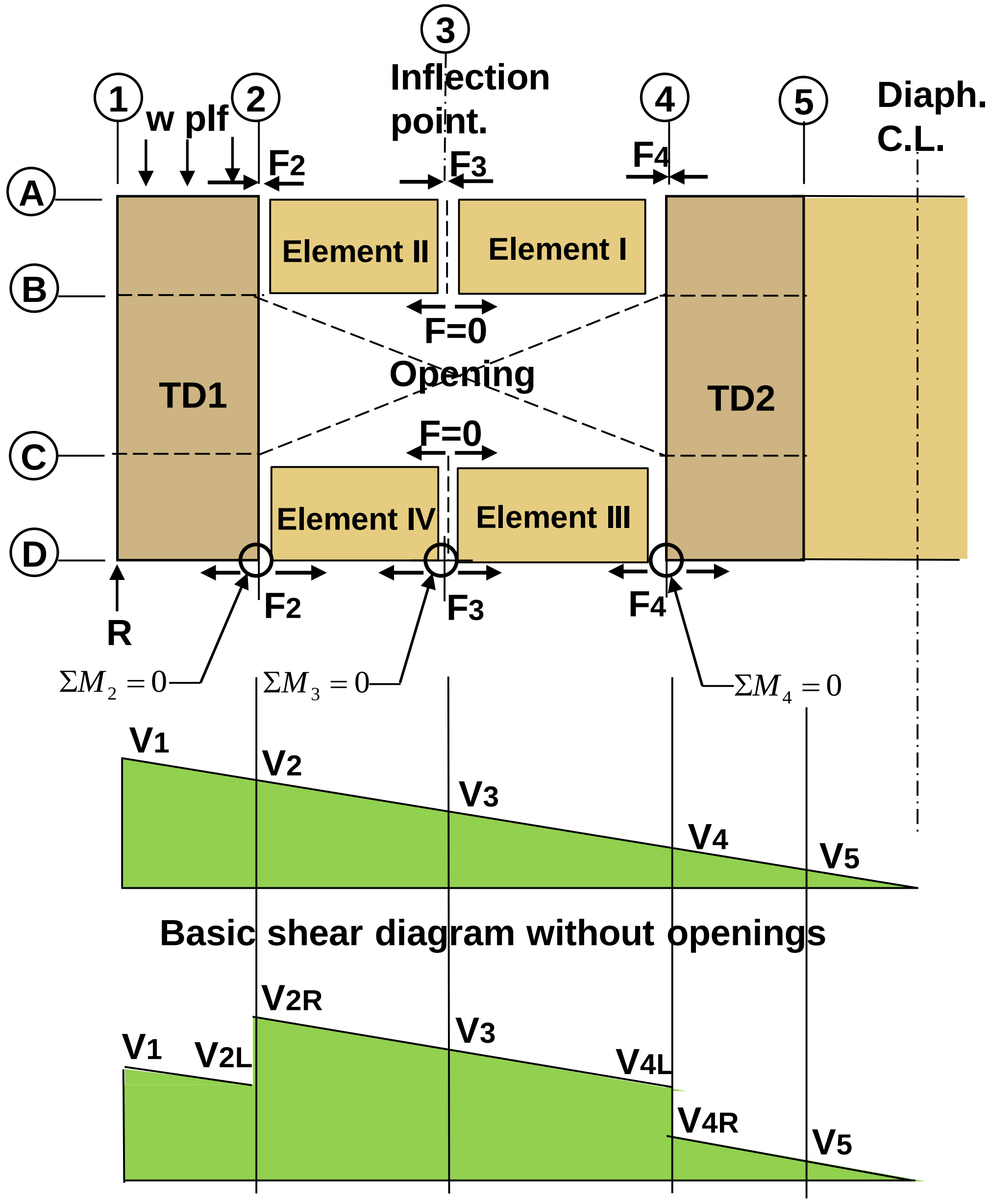
- Diaph. with opening
- Diaphragm w/ interior offset



<u>ATC 7, Diekmann, FPInnovations</u>

If the sections above, below or on each side of the opening does not meet code aspect ratio limits it should be ignored (not stiff enough).

Aspect Ratio Issues



Basic Shear Diaphragm With Opening

__Typical method of analysis (APA Report 138), ATC-7, and FPInnovations__

1. Calculate the chord forces at grid lines 2, 3, and 4 using FBD's.
2. Determine the basic diaphragm shears without an opening.
3. Determine the diaphragm shears with an opening.
4. Break the sections above and below the opening into elements as shown.
5. Determine the local forces at each corner of each segment by FBD's.
6. Determine the net resulting shears and forces (+/-) by combing the shears with and without an opening using a table .

__Using the visual shear transfer method__

1. Determine shear (V_4) at grid line 4.
2. Break the sections above and below the opening into elements as shown.
3. Calculate the chord force at grid line 3.
4. Starting at grid line 4 and moving to the left, sum forces at each corner of each segment to determine the local forces, by FBD's.
5. Calculate all chord, collector forces, and transfer diaphragm shears and forces using the visual shear transfer method.

Opening Analysis-Diekmann method

Example 6-Pop-up Roof Section

A/R main diaphragm and upper section=3.33:1

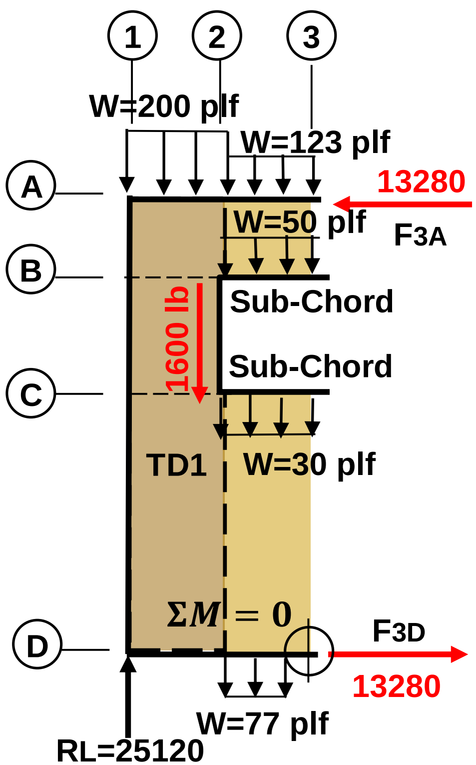
A/R TD1=TD2=3.0:1 o.k.

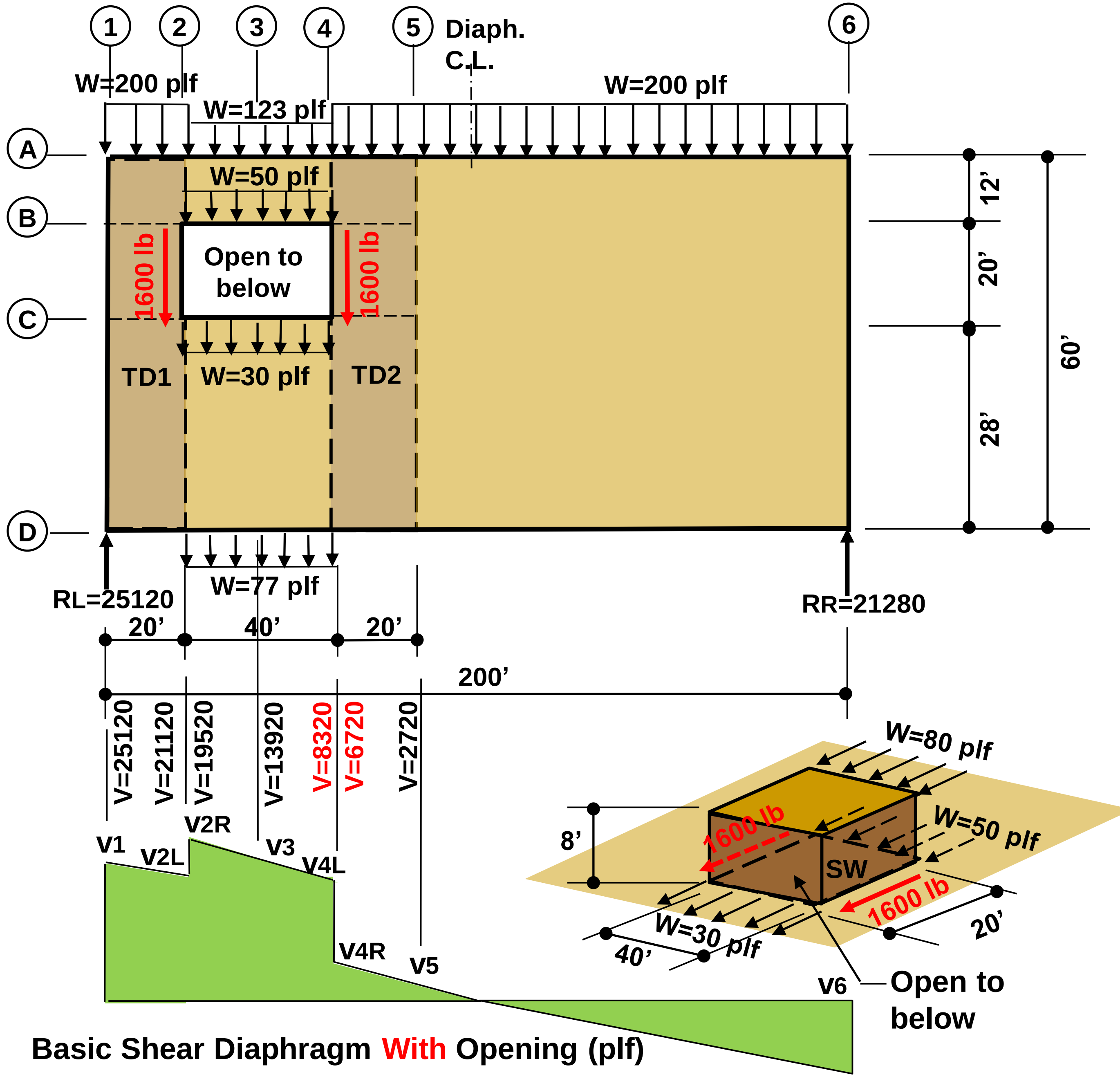
Wind Loads (ASD)

Main
W=200 plf

At opening
Ww=123 plf
Lw=77 plf

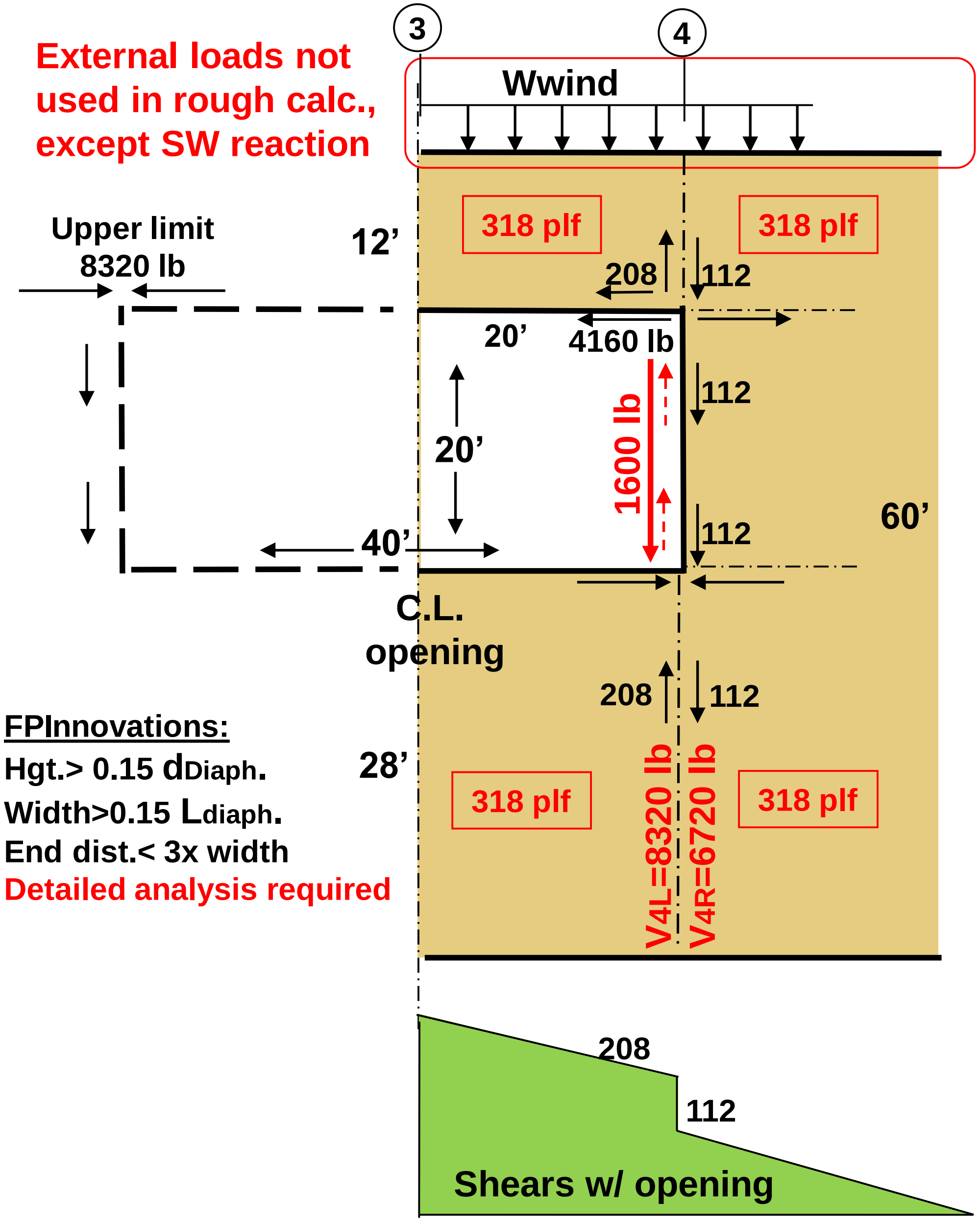
At pop-up (20 psf)
Ww=50 plf
Lw=30 plf





Basic Shear Diagraphm With Opening (plf)

External loads not used in rough calc., except SW reaction



40’ W x 20’ H Opening

FPInnovations:

Hgt.> 0.15 dDiaph.

Width>0.15 Ldiaph.

End dist.< 3x width

Detailed analysis required

$$\text{Unit shear right} = \frac{6720}{60} = 112 \text{ plf}$$

$$\text{Unit shear left} = \frac{8320}{40} = 208 \text{ plf}$$ (includes 1600 lb.)

$$F_V = \frac{112(20)}{2} = 1120 \text{ lb}$$

$$L_V = \frac{1120}{(318-208)} = 10.2 < 20 \text{ o.k.}$$ Also < 12’ header depth, o.k.

$$F_H = 208(20) = 4160 \text{ lb}$$ Lower bound for right collector

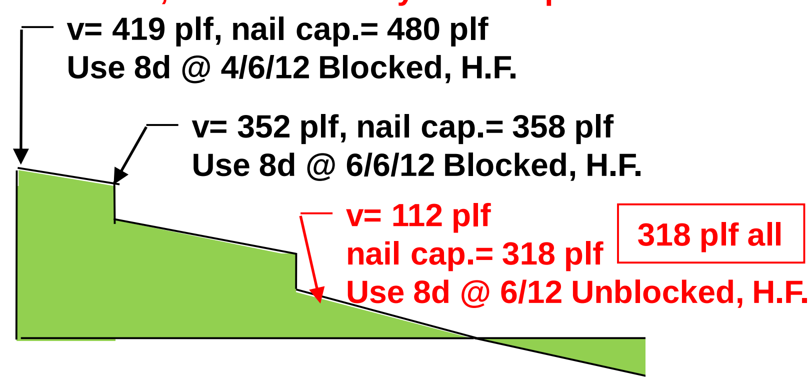
$$L_H = \frac{4160}{(318-112)} = 20.2 < 40' o.k.$$ ≈ DTD

Detailed analysis is not required

However, a check for the upper bound (left side of opening will produce :

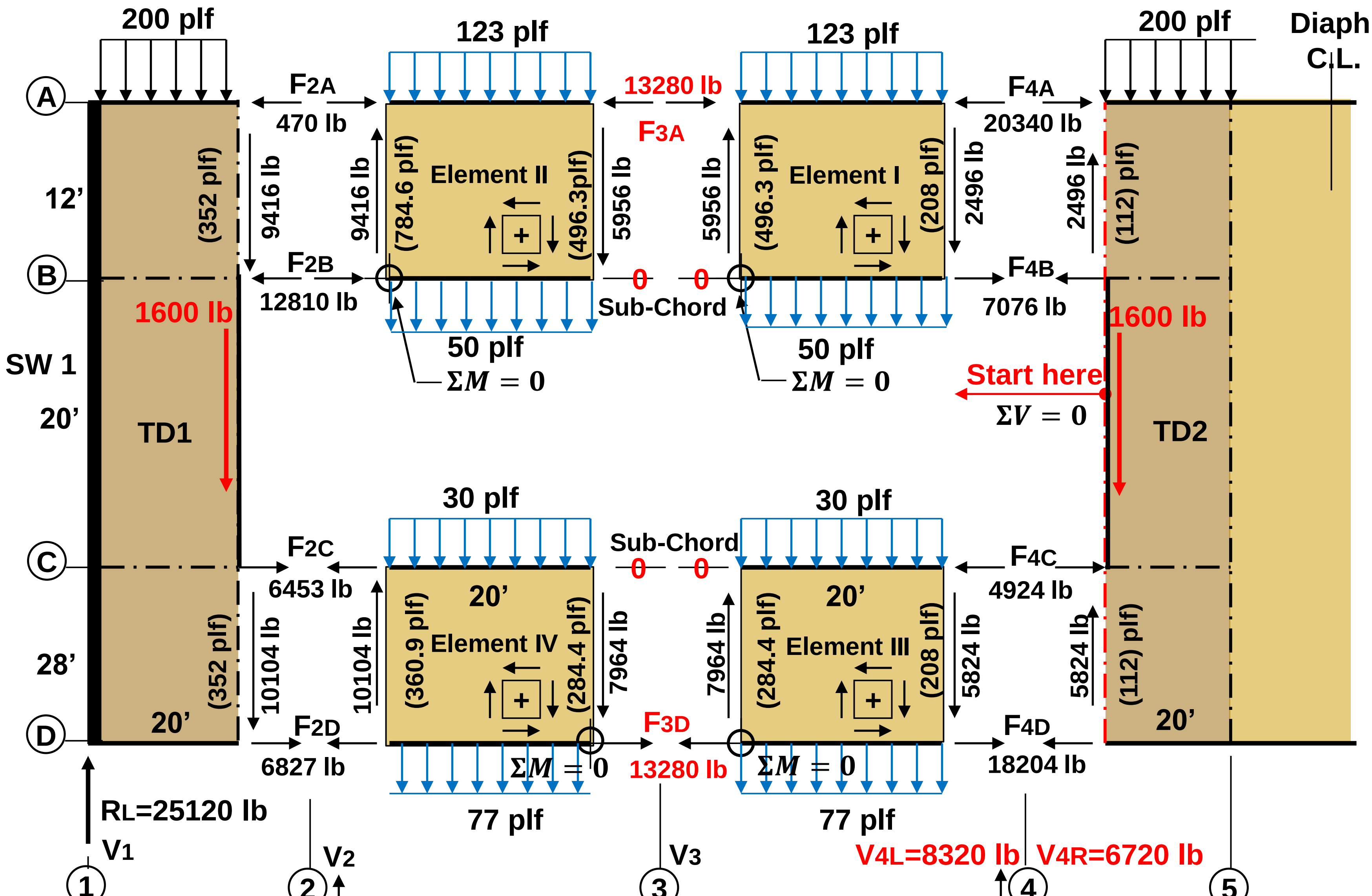
- Increased nailing
- Vertical and horizontal collector lengths > opening width and height

Therefore, a detailed analysis is required



Basic Shear Diagram Without Opening (plf)
Nailing Pattern (ASD Values)

Check If Size and location of Opening in Diaphragm is Critical



$\Sigma V_2 = 10104 + 9416 + 1600 = 21120$ Lb

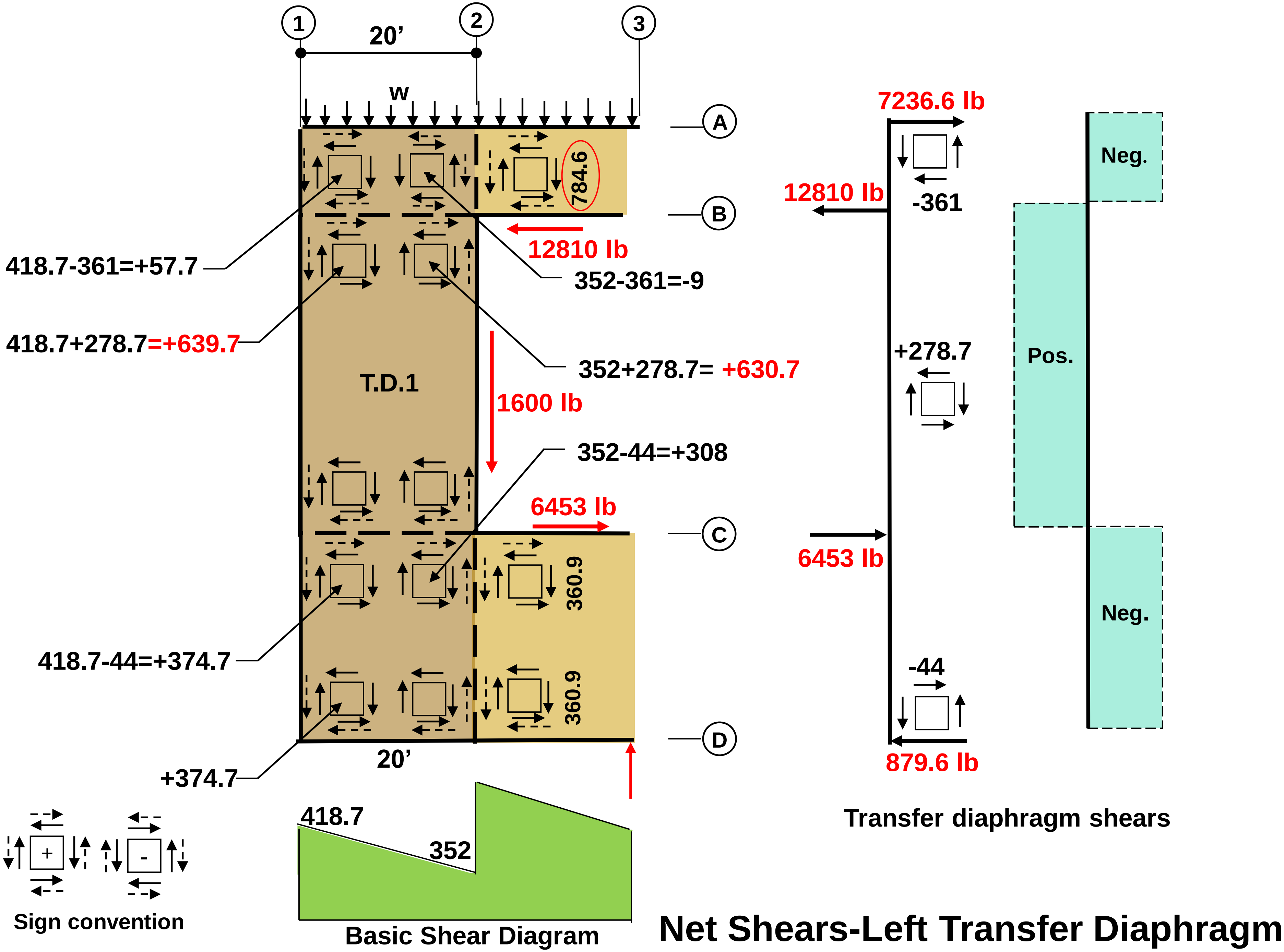
$\Sigma V_3 = 7964 + 5956 = 13920$ Lb

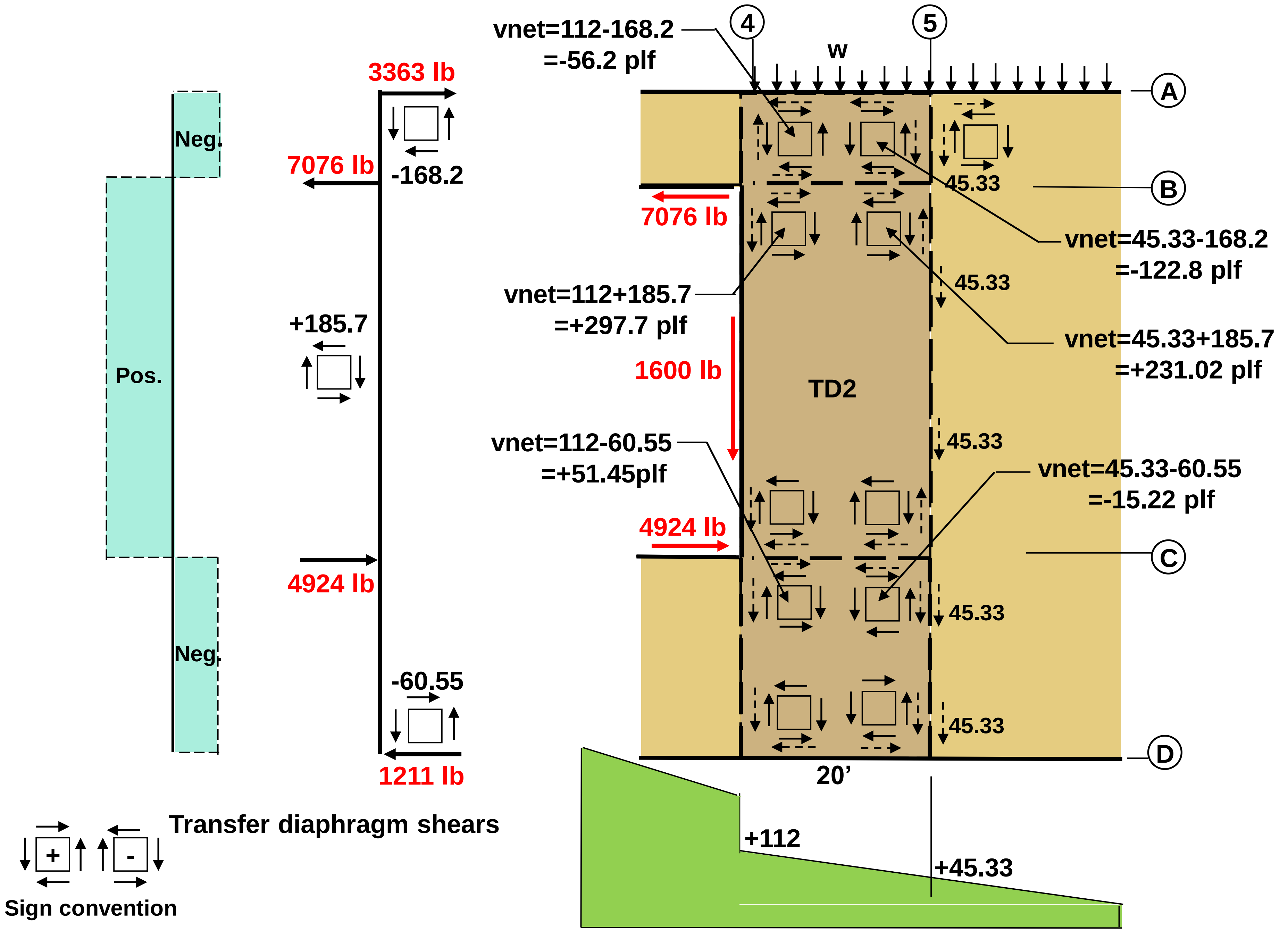
$\Sigma V_4 = 5824 + 2496 = 112(60) + 1600 = 8320$ Lb

The sum of the section shears must match the basic diaphragm shear Values without an opening, ∑V=0.

Free-body of Chord Forces and Segment Forces

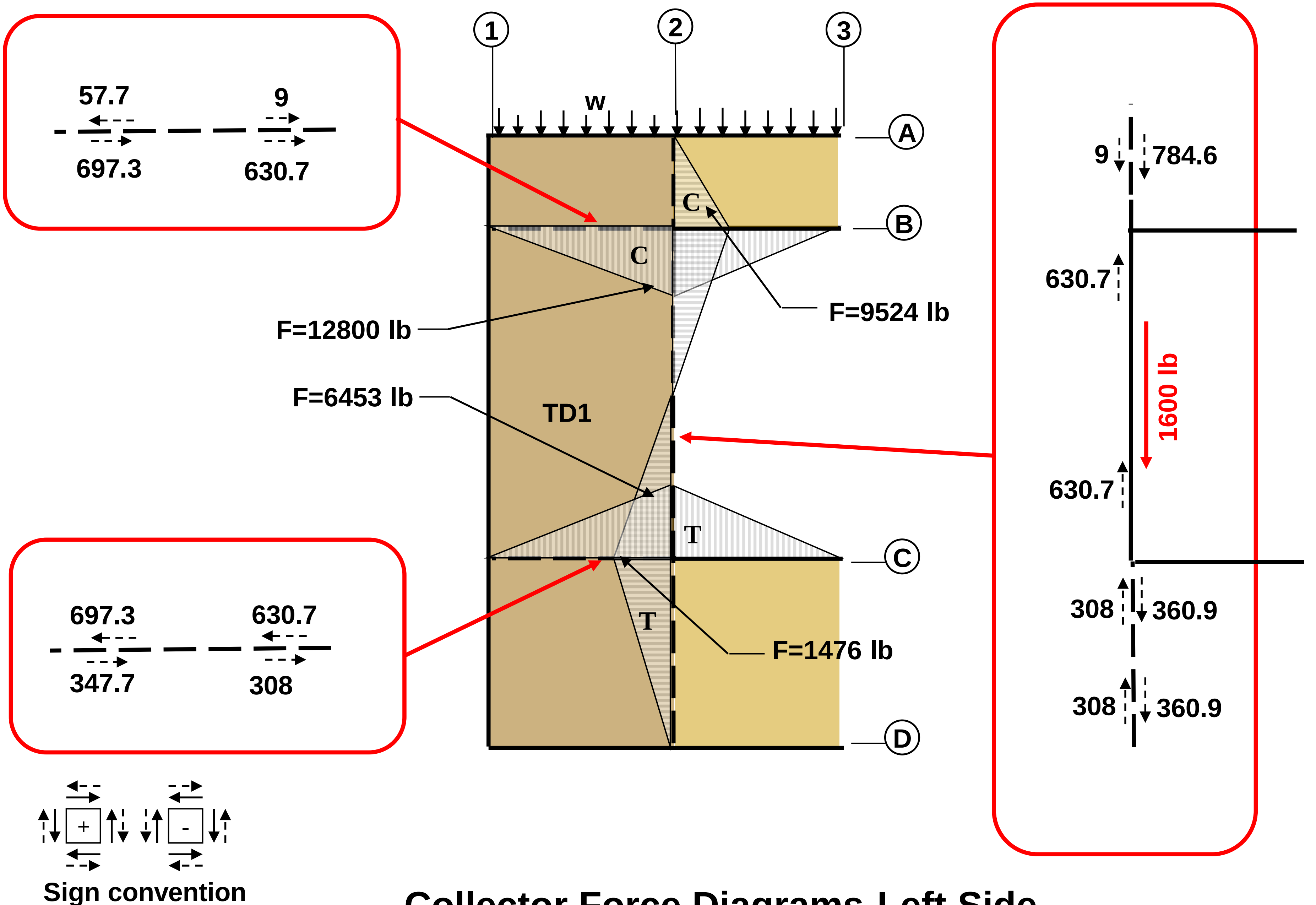
Net Shears-Left Transfer Diaphragm



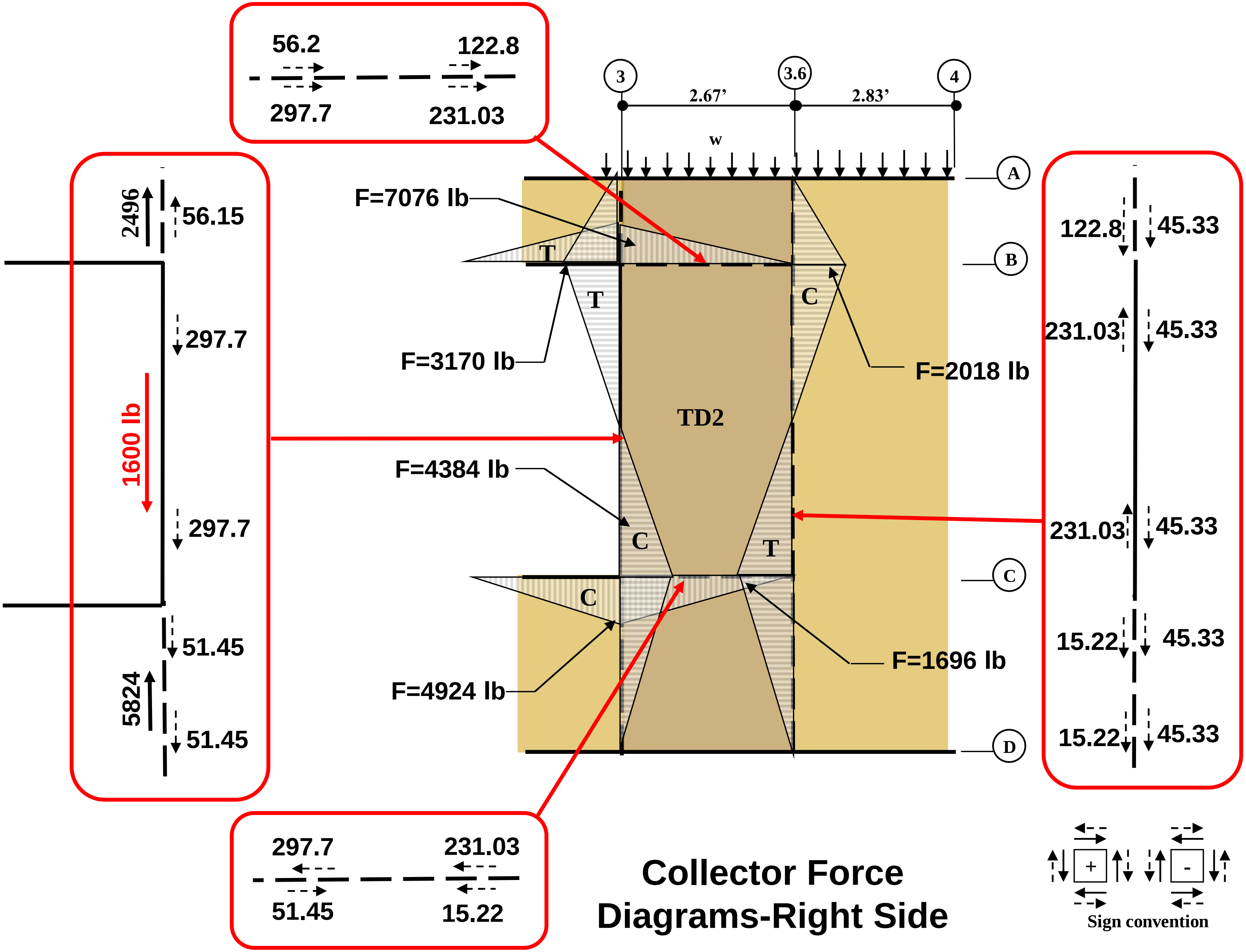


Net Shears-Right Transfer Diaphragm

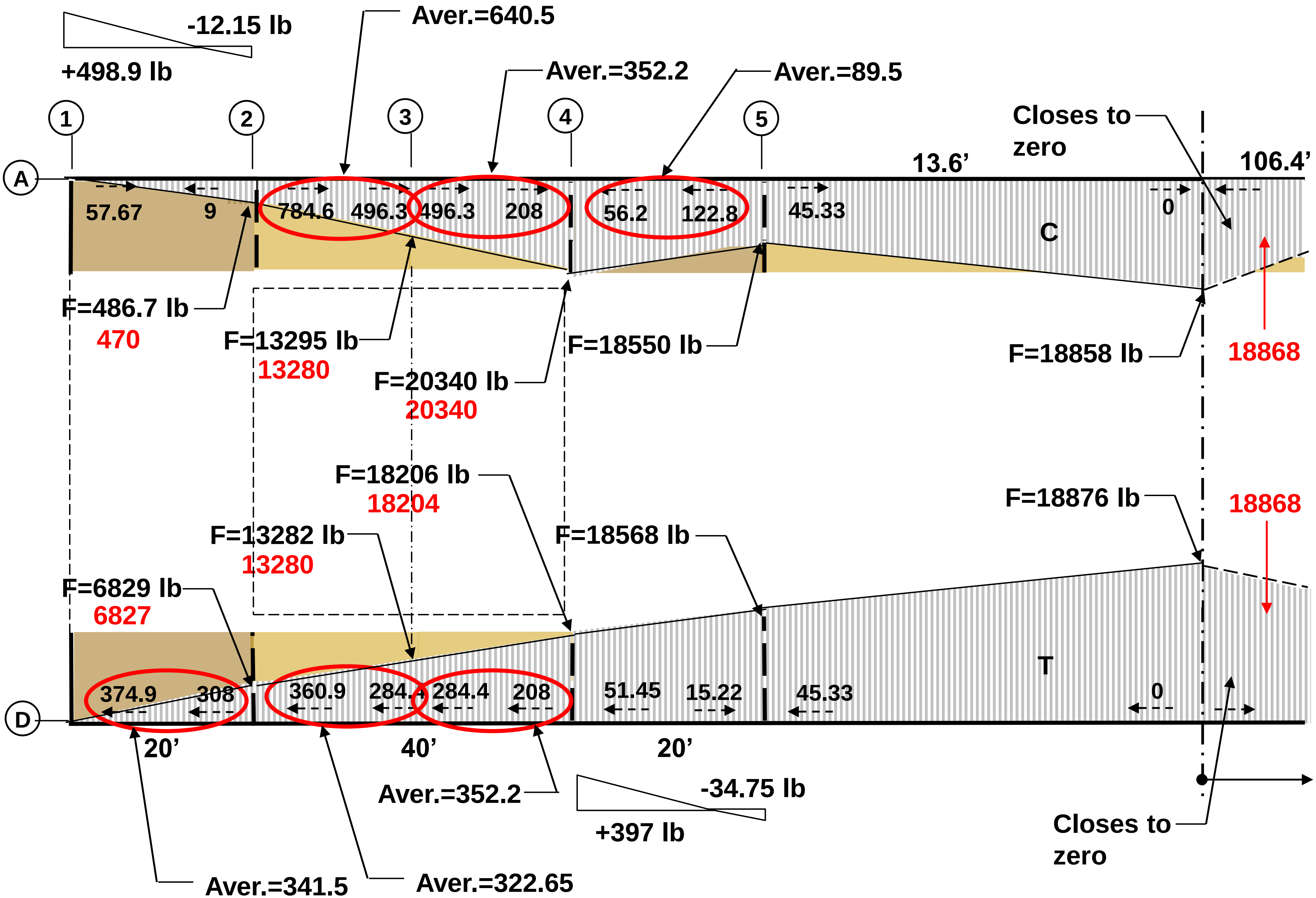
Basic Shear Diagram



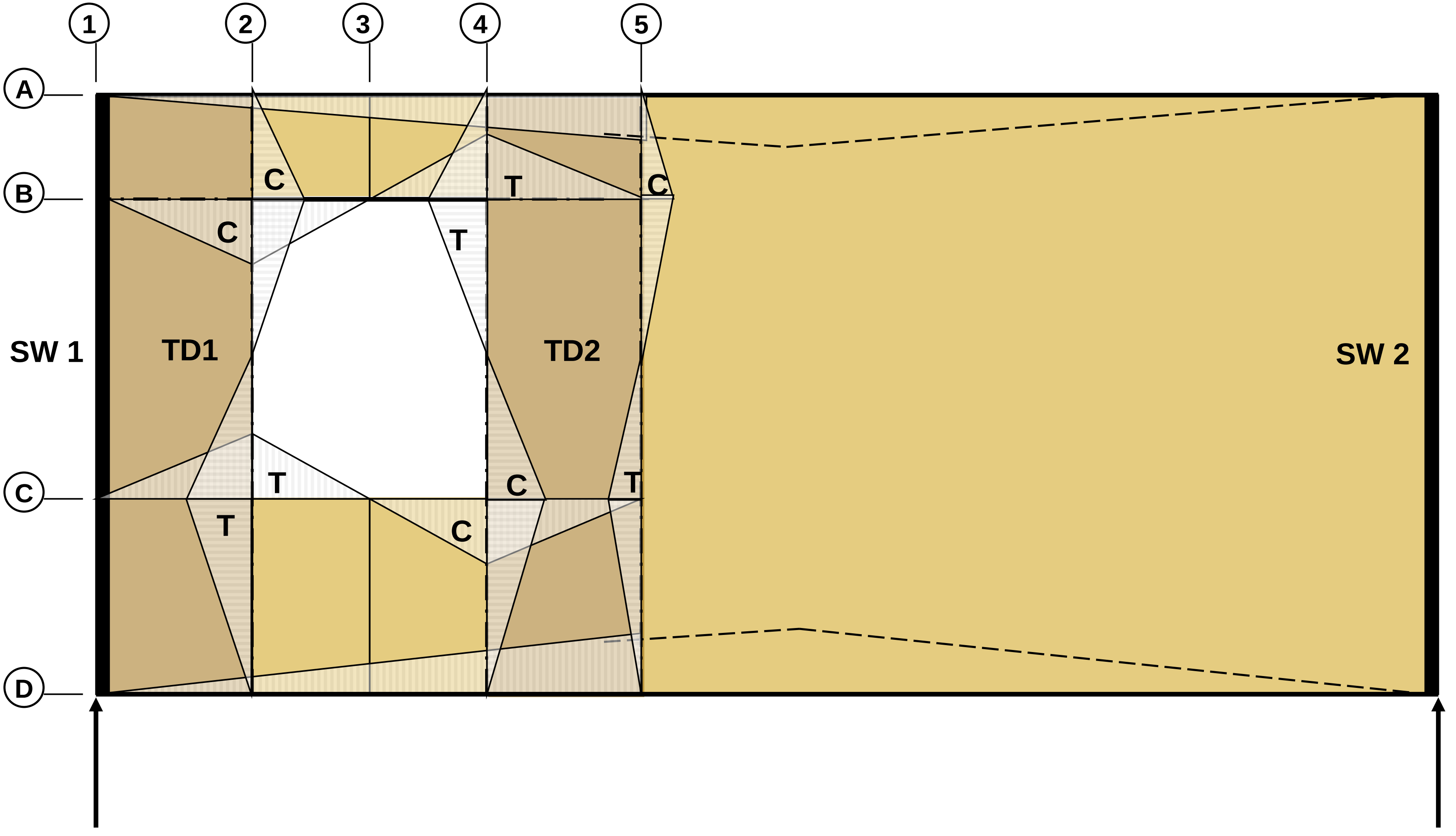
Collector Force Diagrams-Left Side



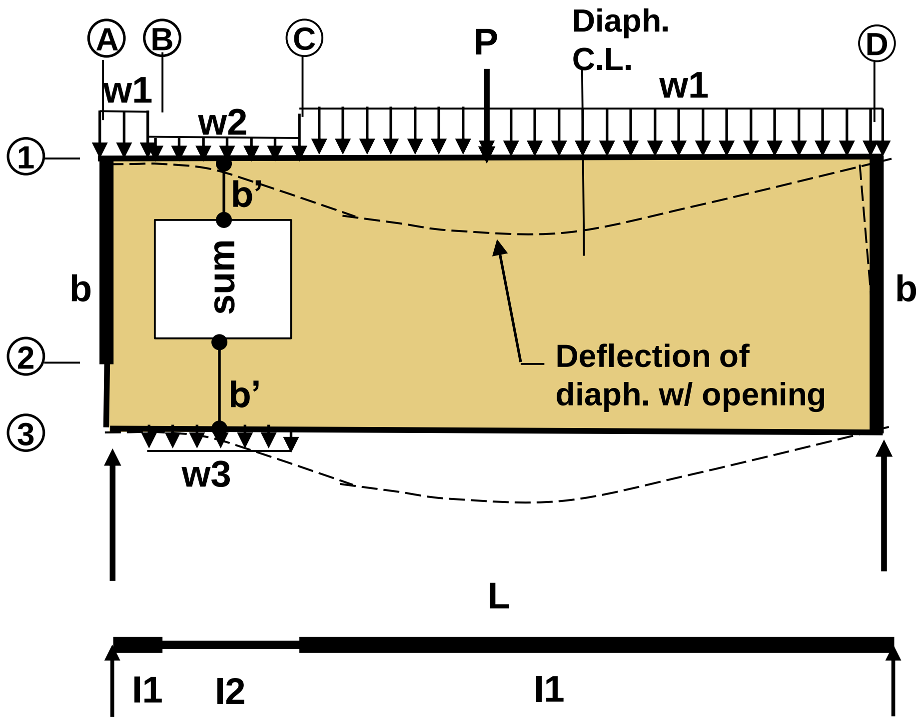
Collector Force Diagrams-Right Side



Chord Force Diagrams



Final Strut/Chord Force Diagrams



Diaphragm Deflection Equations

Equation variables for offset diaphragms

- Varying uniform loads
- Concentrated loads from discontinuous shear walls
- Varying moments of inertia

ATC7

- Modify the bending and shear portion of the standard rectangular deflection equation to fit the model, where:

$$\Delta_{TL} = \Delta_B + \Delta_S + 0.188 L e_n + \frac{\Sigma(\Delta_C X)}{2b}$$

where

$$\Delta_B = \int_a^b \frac{mM}{EI_1}dx + \int_b^c \frac{mM}{EI_2}dx + \int_c^d \frac{mM}{EI_1}dx, \text{ and}$$

$$\Delta_S = \frac{bt}{2GA^2}\left[\int_a^b wx\,dx + \int_b^c \frac{wx}{\left(\frac{b'}{b}\right)^2}dx + \right.$$

SDPWS combines

$$\Delta_{TL} = \frac{5vL^3}{8EAb} + \frac{vL}{4G_t} + 0.188 L e_n + \frac{\Sigma(\Delta_C X)}{2b}$$

Cannot use

IBC Eq. 23 – 1

Bending deflection

Shear deflection

Nail slip Adjusted for non-uniform nailing (ATC-7/APA)

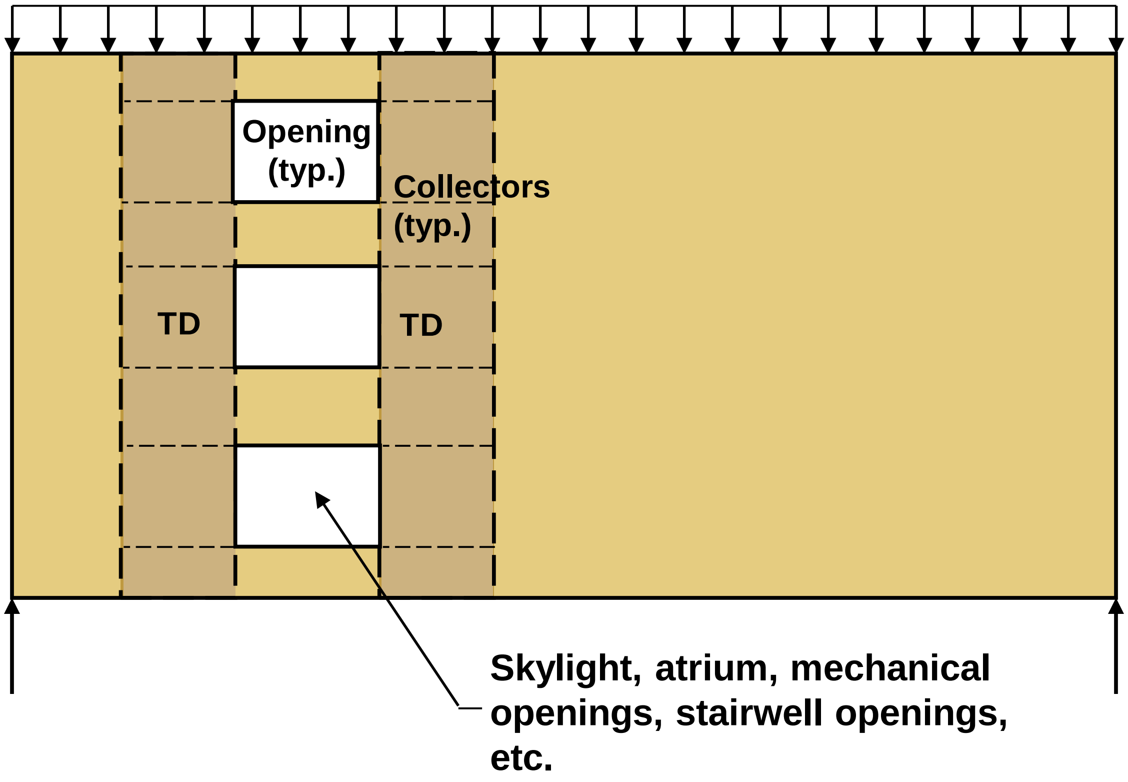
Chord slip

Standard deflection equation for simple span, rectangular, rigid supports, fully blocked, uniformly loaded, constant cross section (Δ at C.L.)

Shear Deflection -USDA Research Note FPL-0210

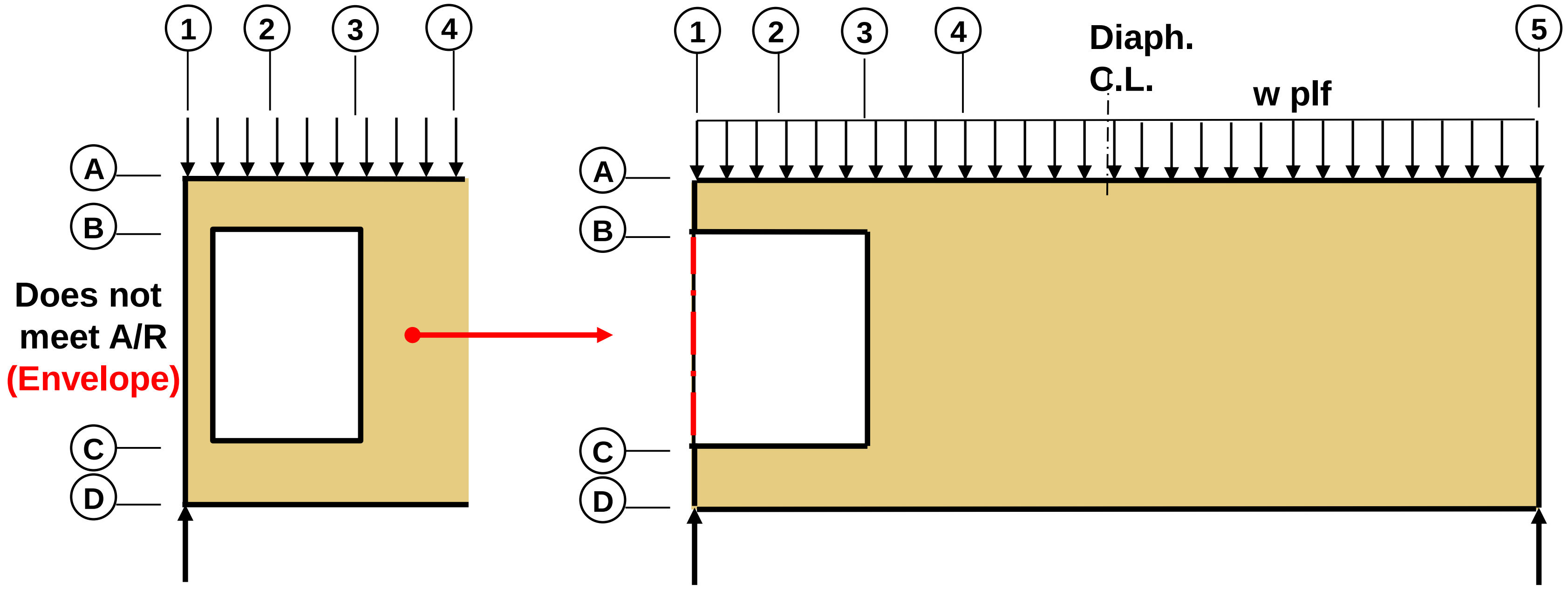
- Simplification of the conventional energy method
- The integrations of the equations can be reduced to multiplying the total area of the shear diagram due to the general loading by the ordinate of the shear diagram due to a dummy load applied at the desired point of shear deflection.

NOTE: Multiply deflection x 2.5 for unblocked diaphragm
Multiply nail slip by 1.2 if not Structural I plywood

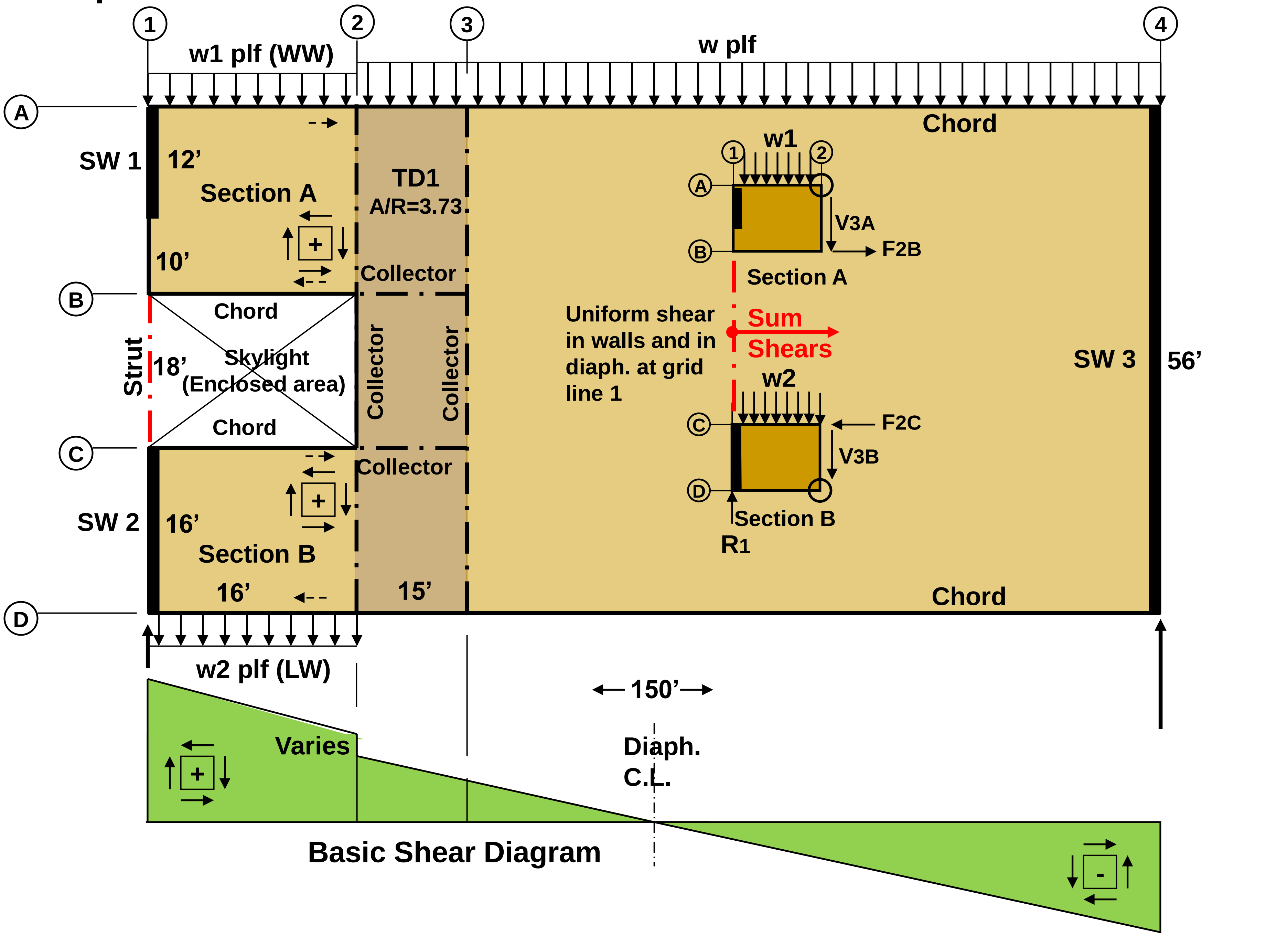


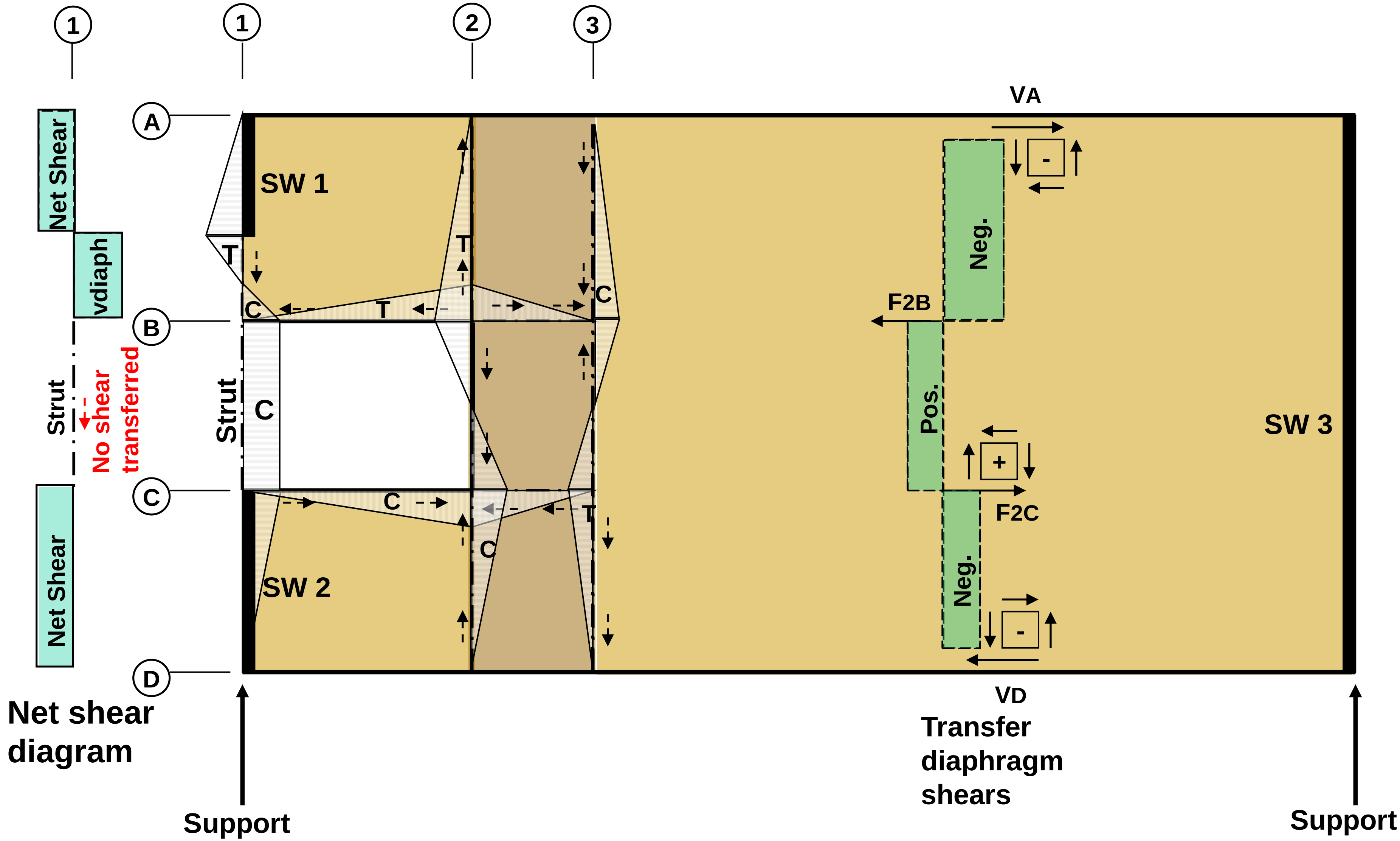
Multiple Opening Issues

End Openings



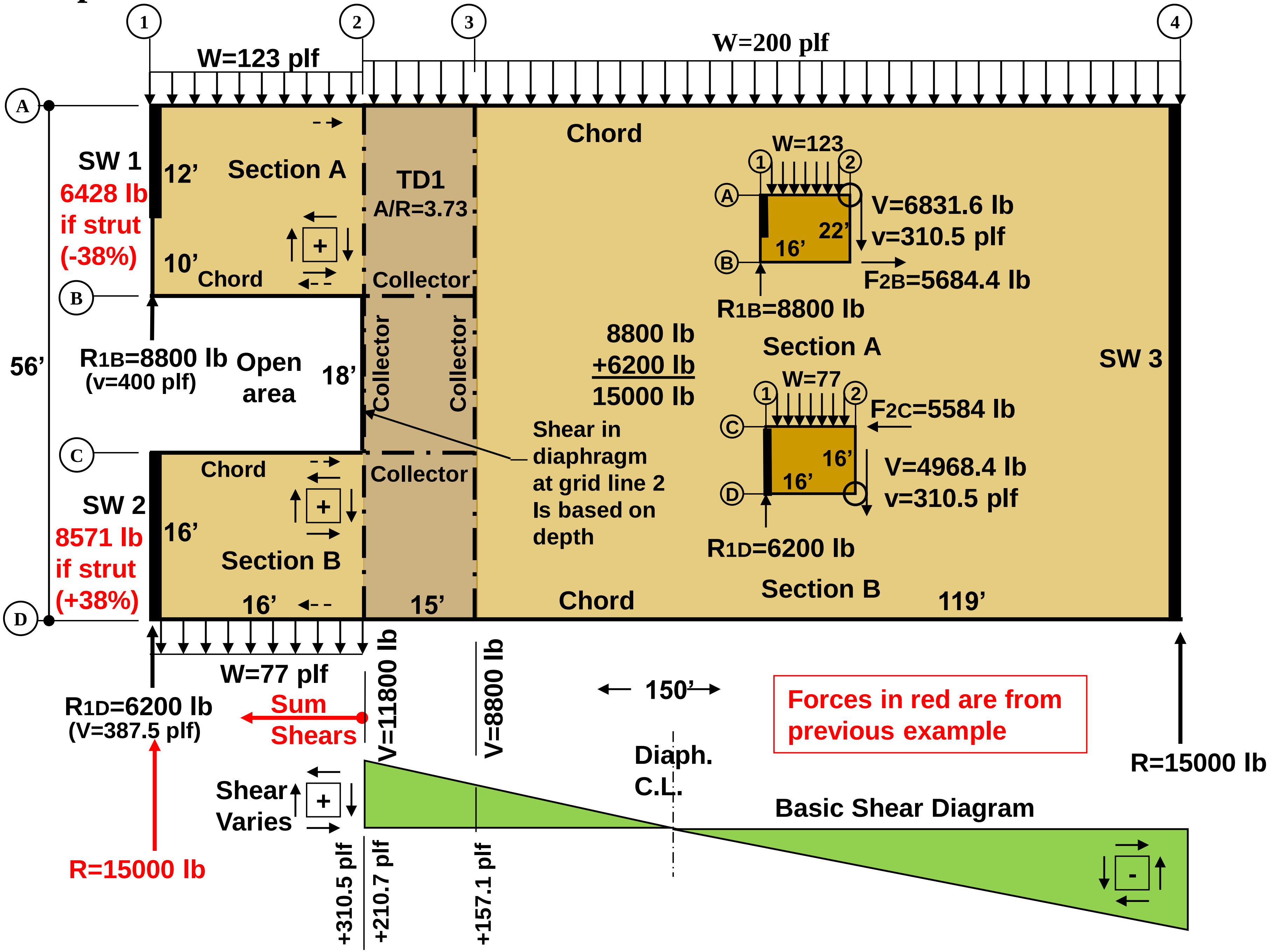
Example 7- Intermediate Horizontal Offset at End Wall With Strut

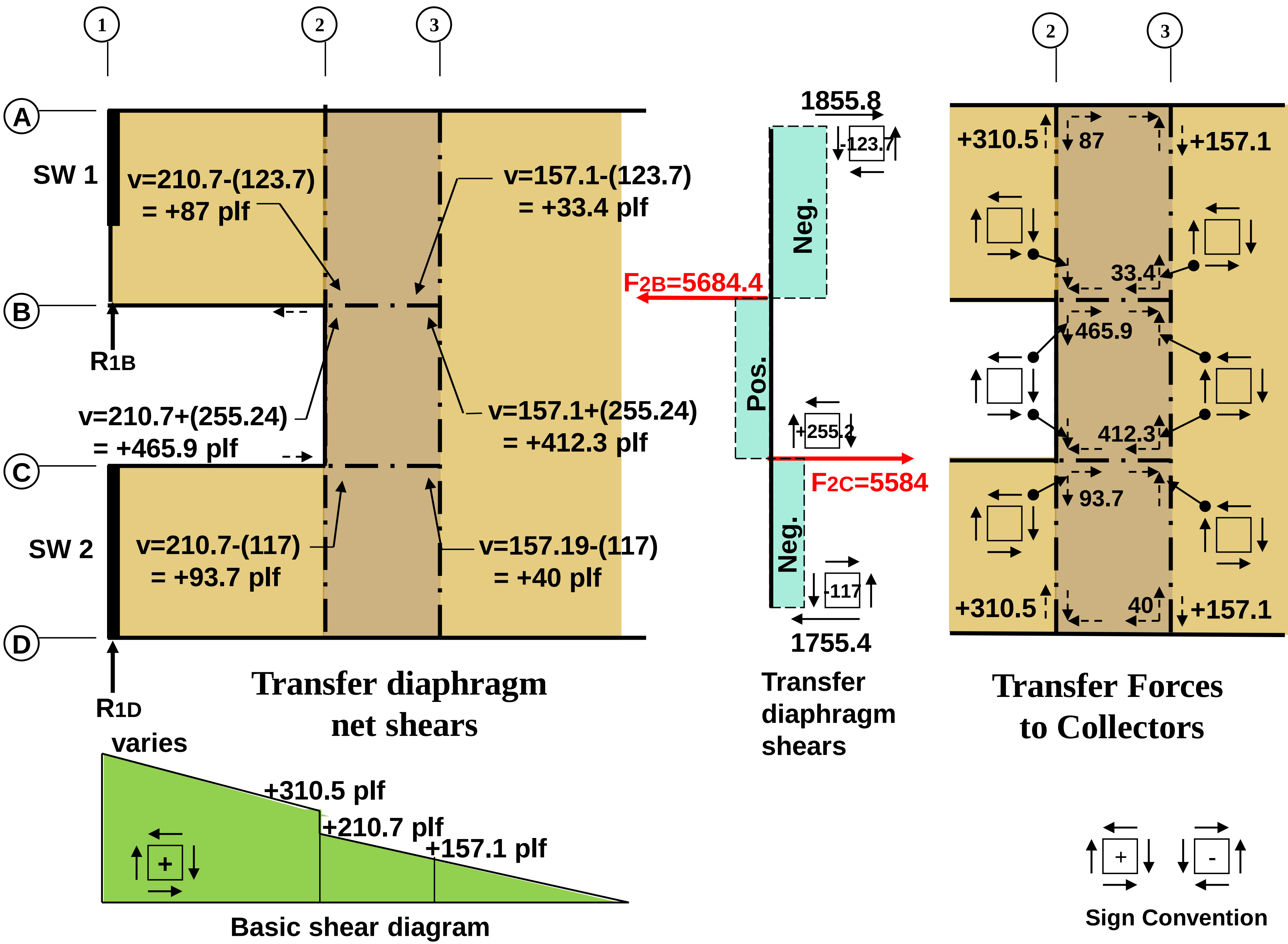




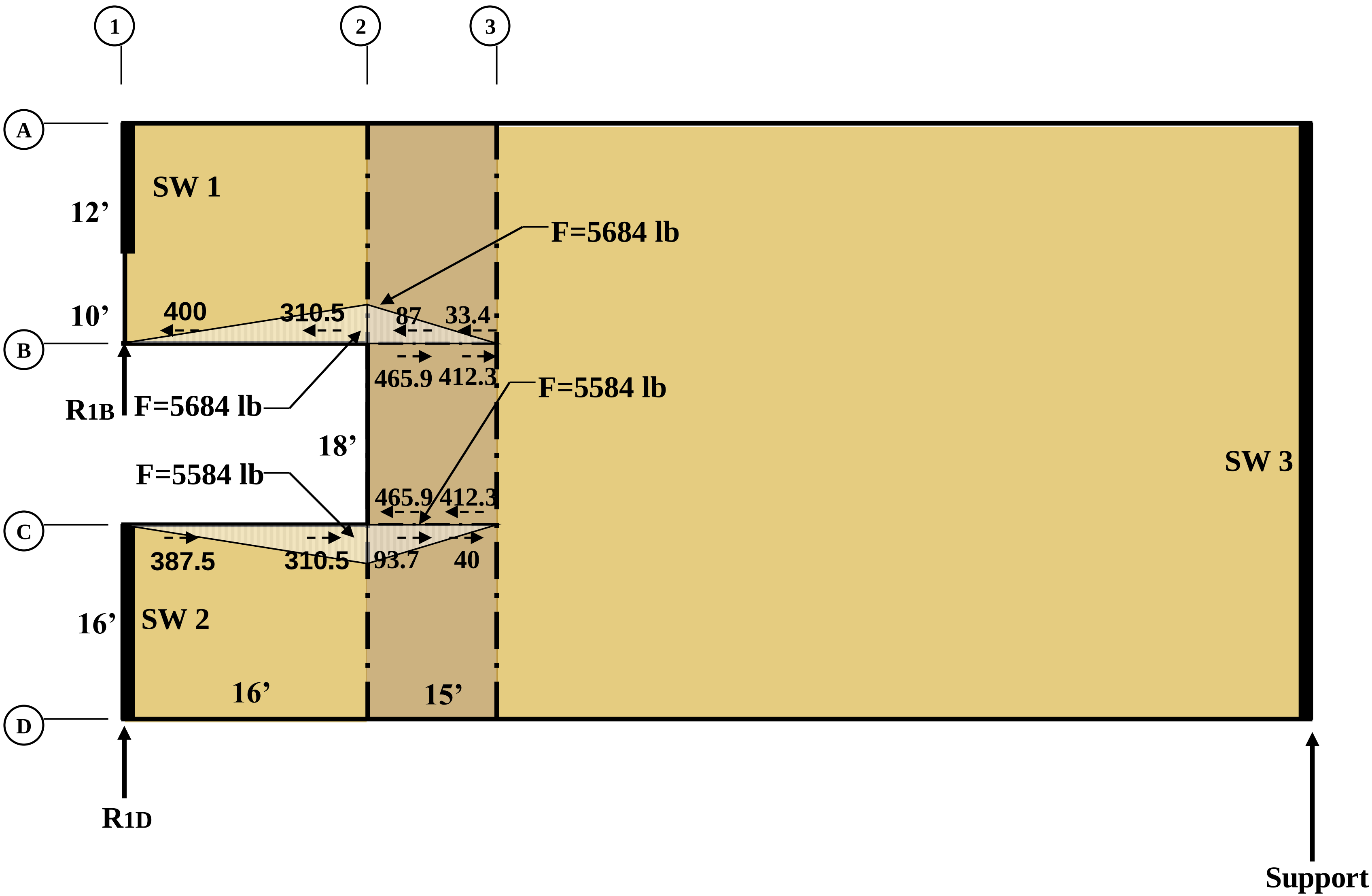
Resulting Strut, Collector and Chord Force Diagrams if Strut

Example 8 -Intermediate notch at End Wall Without Strut

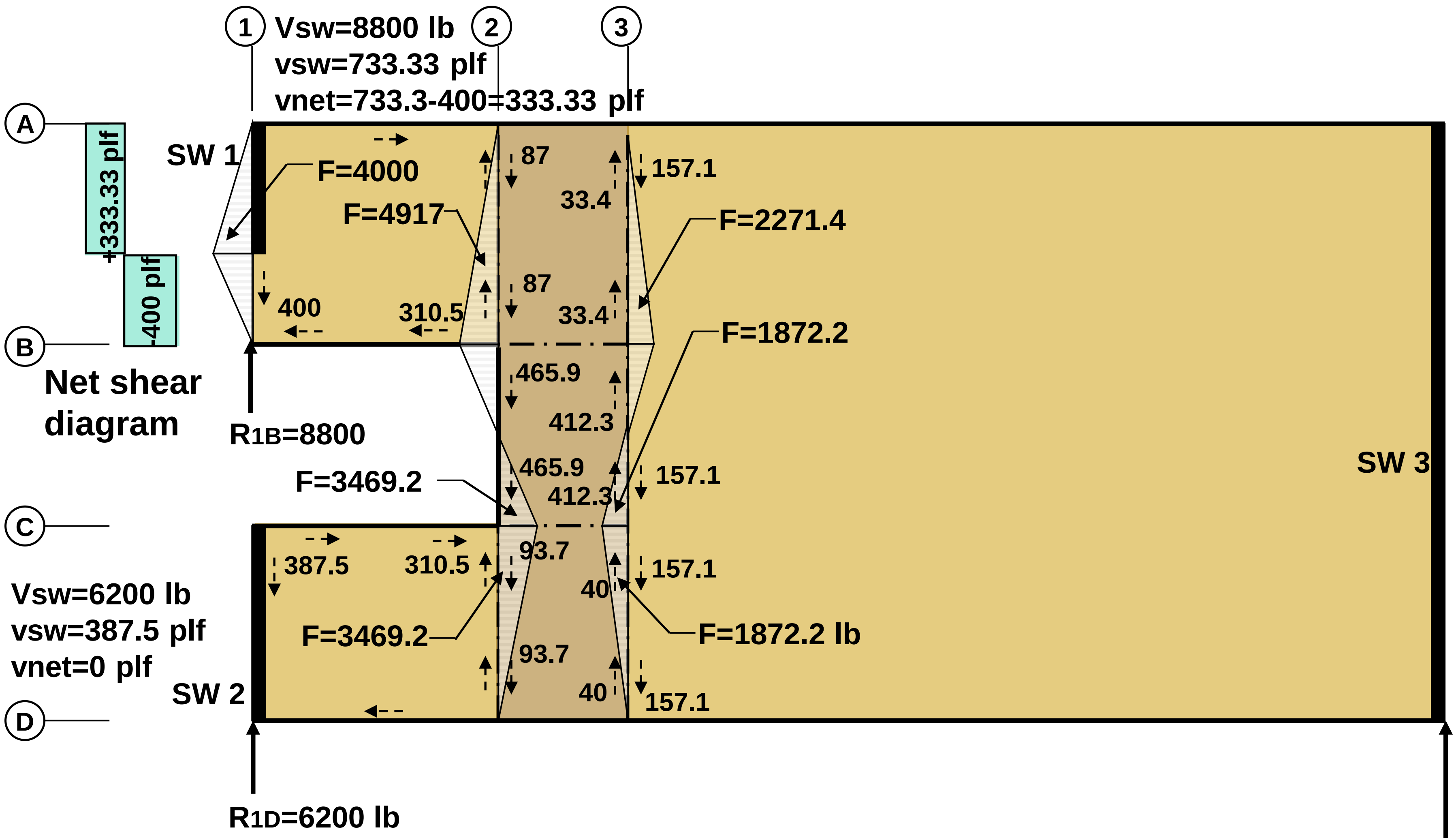




Transfer diaphragm and net diaphragm shears



Longitudinal Chord Force Diagrams



Traverse Strut/Collector Force Diagrams

Relevant 2015 SPDWS Sections

(Diaphragm Stiffness, Distribution of Shears and Open Front / Cantilever Diaphragms)

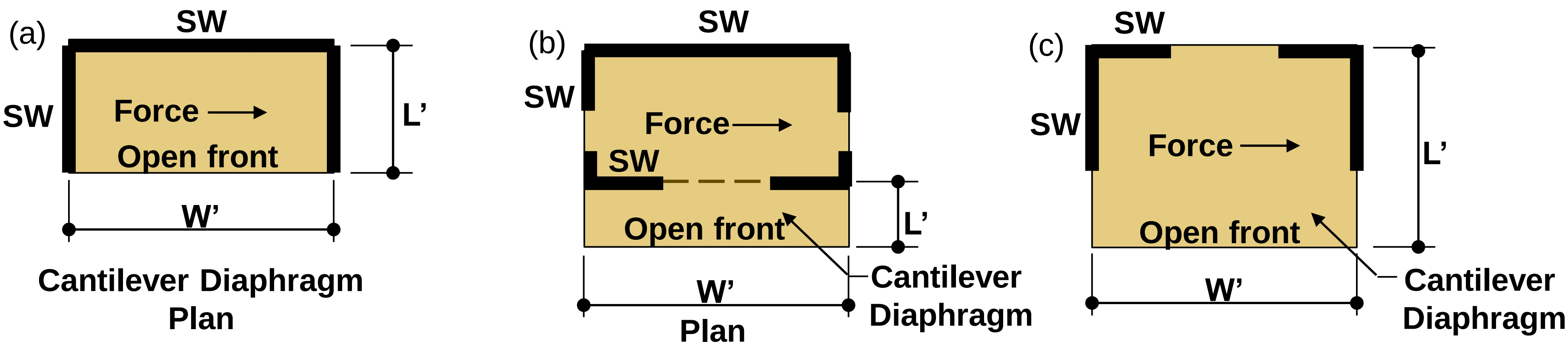


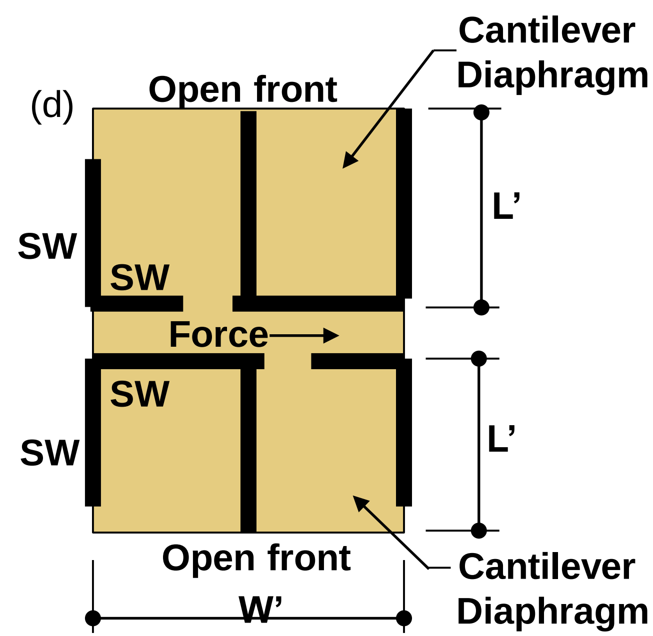
Figure 4A Examples of Open Front Structures

New definitions added:

- Open front structures
- Notation for L' and W' for cantilever Diaphragms
- Collectors

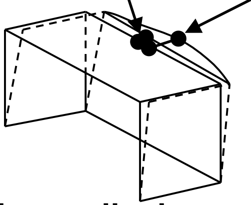
Relevant Revised sections:

- 4.2.5- Horizontal Distribution of Shears
- 4.2.5.1-Torsional Irregularity
- 4.2.5.2- Open Front Structures



4.2.5 Horizontal Distribution of Shear (Revised)

Distribution of shear to vertical resisting elements shall be based on:



Maximum diaphragm deflection (MDD) >2x average story drift of vertical elements, using the ELF Procedure of Section 12.8?

Calculated as Flexible

- **Analysis where the diaphragm is modeled as :**
  - Idealized as flexible-based on tributary area.
    - Can under-estimate forces distributed to the corridor walls (long walls) and over-estimate forces distributed to the exterior walls (short walls)
    - Can inaccurately estimate diaphragm shear forces
  - Idealized as rigid
    - Distribution based on relative lateral stiffnesses of vertical-resisting elements of the story below.
    - Can be idealize as rigid when the computed maximum in-plane deflection of the diaphragm is less than or equal to two times the average deflection of adjoining vertical elements of the LFRS under equivalent tributary lateral load.
    - More accurately distributes lateral forces to corridor, exterior and party walls
    - Allows better determination of building drift
  - Modelled as semi-rigid.
    - Not idealized as rigid or flexible
    - Distributed to the vertical resisting elements based on the relative stiffnesses of the diaphragm and the vertical resisting elements accounting for both shear and flexural deformations.
    - It shall be permitted to use an enveloped analysis -Larger of the shear forces resulting from analyses where idealized as flexible and idealized as rigid (Minimum analysis).

Note:
Offsets in diaphragms can also affect the distribution of shear in the diaphragm due to changes in the diaphragm stiffness.

4.2.5.2 Open Front Structures: (Figure 4A)

For resistance to seismic loads, wood-frame diaphragms in open front structures shall comply with all of the following requirements:

1. **The diaphragm conforms to:**
   a. **WSP-L'/W' ratio ≤ 1.5:1 4.2.7.1**
   b. **Single layer-Diag. sht. Lumber- L'/W' ratio ≤ 1:1 4.2.7.2**
   c. **Double layer-Diag. sht. Lumber- L'/W' ratio ≤ 1:1 4.2.7.3**

2. **The drift at edges shall not exceed the ASCE 7 allowable story drift ratio when subject to seismic design forces including torsion, and accidental torsion (Deflection-strength level amplified by Cd.).**

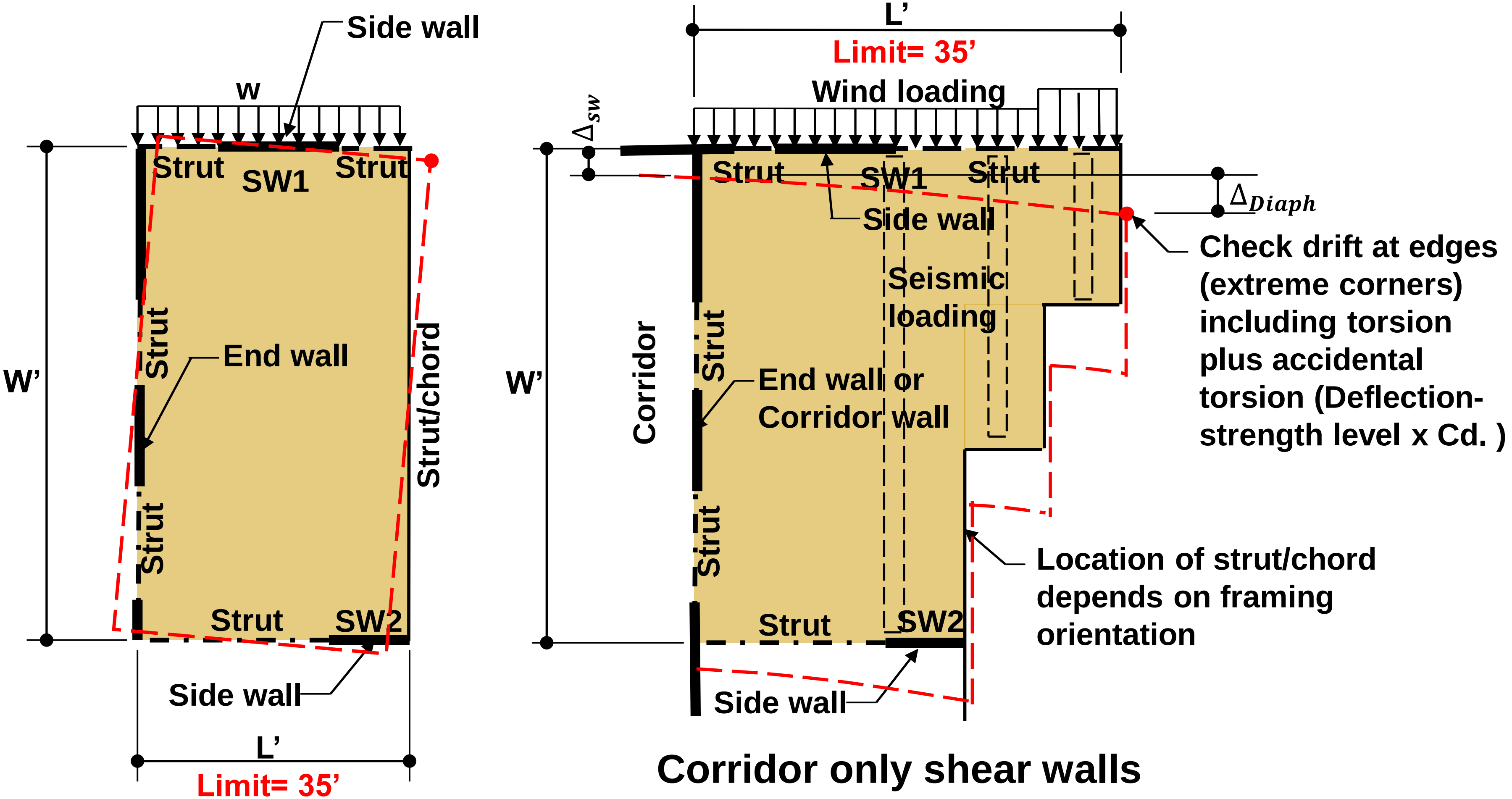
3. **For open-front-structures that are also torsionally irregular as defined in 4.2.5.1, the L'/W' ratio shall not exceed 0.67:1 for structures <u>over one</u> story in height, and 1:1 for structures <u>one</u> story in height.**

4. **For loading parallel to open side:**
   a. **Model as semi-rigid (min.), shall include shear and bending deformation of the diaphragm, or idealized as rigid.**
   b. **Drift at edges of the structure ≤ the ASCE 7 allowable story drift ratio when subject to seismic design forces including torsion, and accidental torsion. Torsion (Deflection-strength level amplified by Cd.)**

5. **The diaphragm length, L', (normal to the open side) does not exceed 35 feet.**
   <u>Exception:</u>
   Where the diaph. edge cantilevers no more than 6' beyond the nearest line of vertical elements of the LRFS.

4.2.5.2.1 For open front structures of 1 story, where L'≤25' and L'/W' ≤1:1, the diaphragm shall be permitted to be idealized as rigid for the purposes of distributing shear forces through torsion.

Example-Open Front Diaphragms

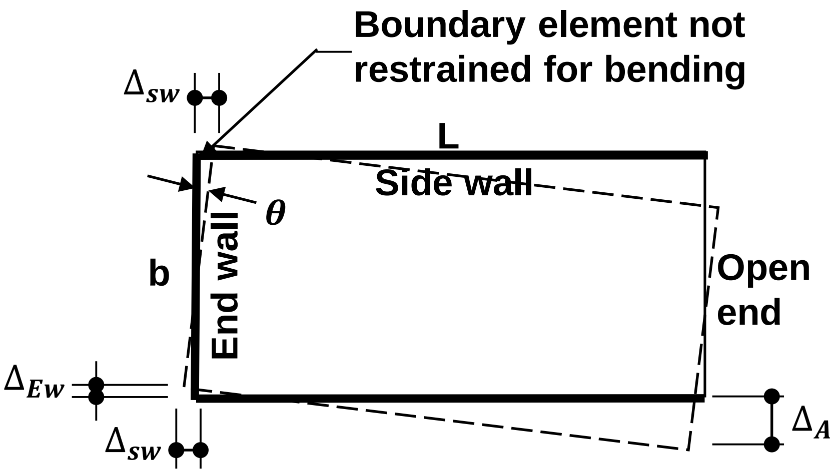


Corridor only shear walls

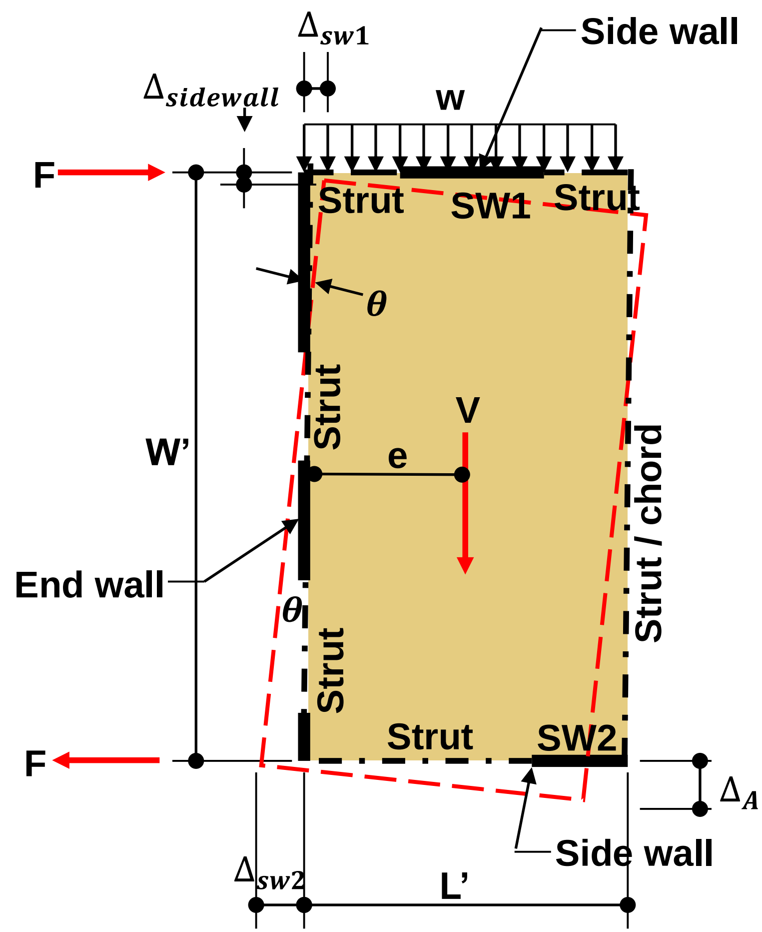
4.2.6.1 Framing requirements:

- Diaphragm boundary elements shall be provided to transmit design tension, compression and shear forces.
- Diaphragm Sheathing shall not be used to splice boundary elements.

Example-Simple Open Front Diaphragm Deflection (APA)



APA Figure



Shear Defl. | Nail slip | rotation | End shear wall lateral translation

$$\Delta_A = \frac{(V_{max})L}{2Gt} + 0.376L' e_n + \frac{2\Delta_{sw}L}{b} + \Delta_{ew}$$

Note:
If there are splices in the struts, chord slip must be added to the deflection equation

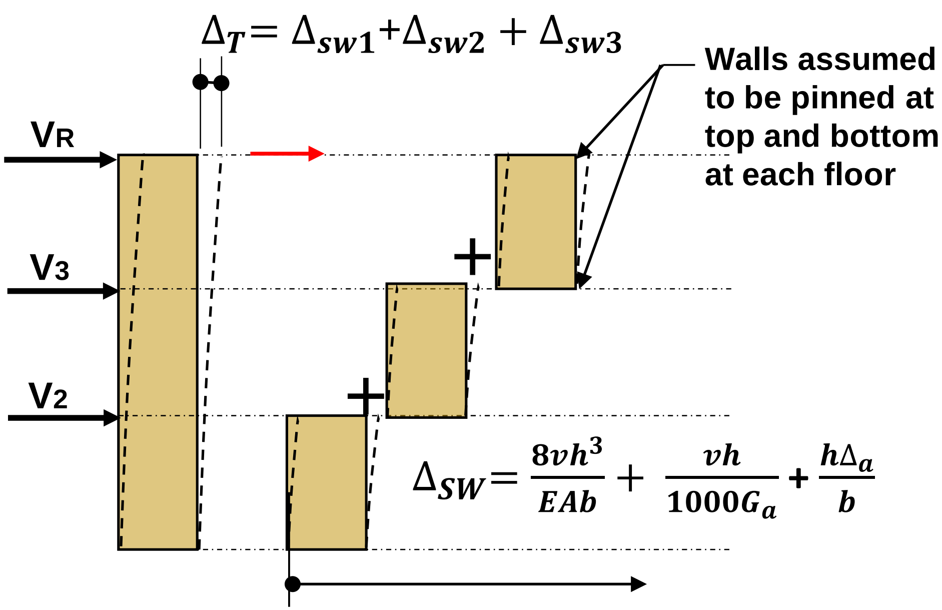
Bending term required if chords cont. across corridor

Rotation term needs to be adjusted if different end wall lengths

Tall Shear Walls

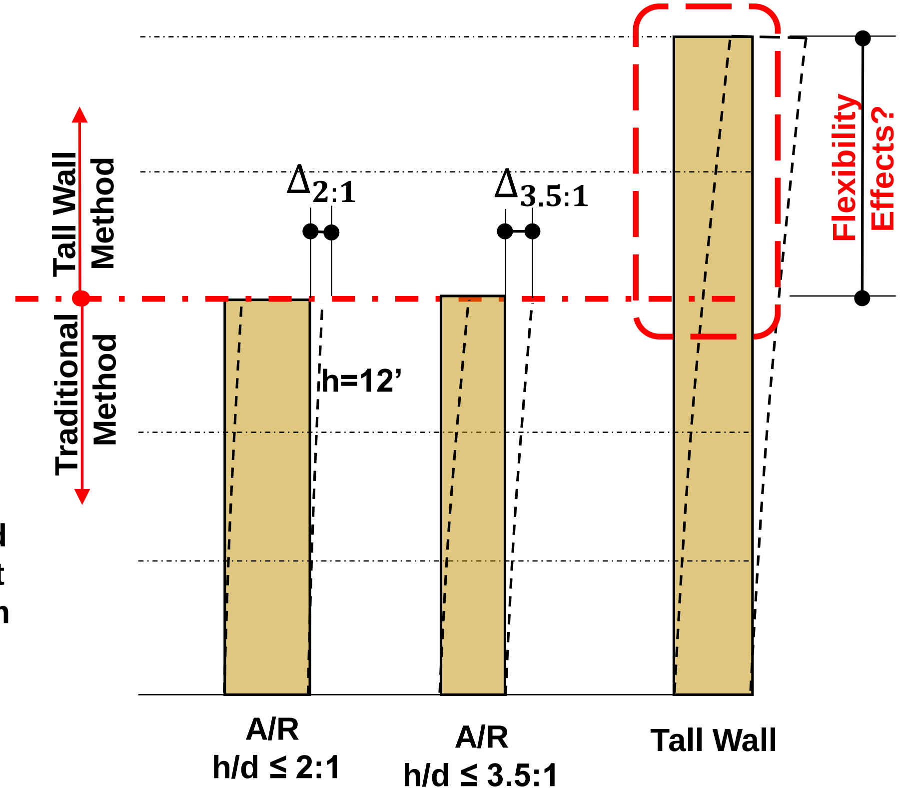
Testing shows that the traditional deflection equation cannot be used for walls with aspect ratios higher than 2:1, because deflections can not be adequately predicted. (Dolan, et. al.)

- Traditional Method good for 3 stories or less.
- Tall walls greater than 3 stories require consideration of flexure and wall rotation.



Not valid for multi-story shear walls

Traditional Method



A/R, Stiffness of Shear Walls

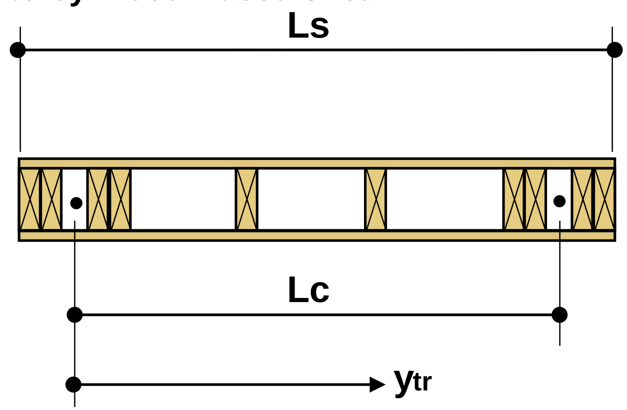
Methods Used:

- Shiotani/Hohbach Method
- Thompson Method
- FPInnovations Method
- Computer model

FPInnovations-Deflections of Stacked Multi-story Shear Walls

"A Mechanics-Based Approach for Determining Deflections of Stacked Multi-Storey Wood-Based Shear Walls", Newfield (metric units)

- **Mechanics based approach**
- **Uses 5 part deflection equation**

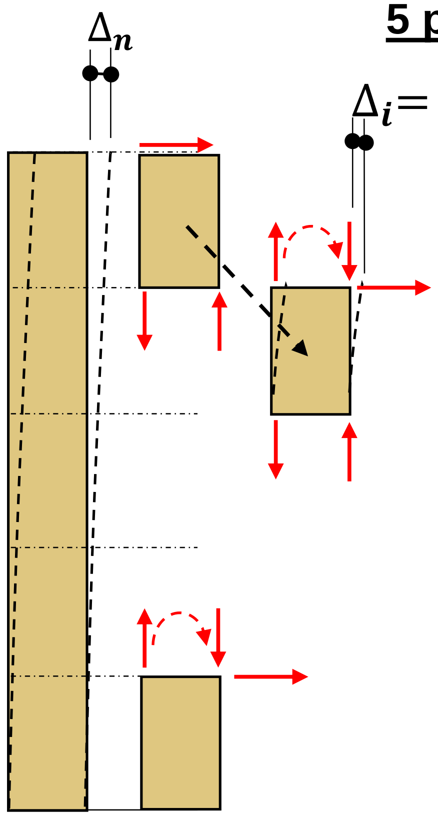


$$I_{tr} = A_{t,tr} \cdot y_{tr}^2 + A_c \cdot (L_c - y_{tr})^2$$

I = discrete hold down

Itr = continuous hold down

Uses transformed composite section where continuous tie down (ATS)



$$V_o = \sum_i^n V_i$$

$$M_o = \sum_i^n V_i H_i$$

5 part deflection equation

$$\Delta_i = \Delta_{b,i} + \Delta_{s,i} + \Delta_{n,i} + \Delta_{a,i} + \Delta_{r,i}$$

Bending ($\Delta_{b,i}$), **Panel Shear** ($\Delta_{s,i}$), **Nail slip** ($\Delta_{n,i}$), **Anchor Elongation** ($\Delta_{a,i}$), **Wall Rotation** ($\Delta_{r,i}$)

Where

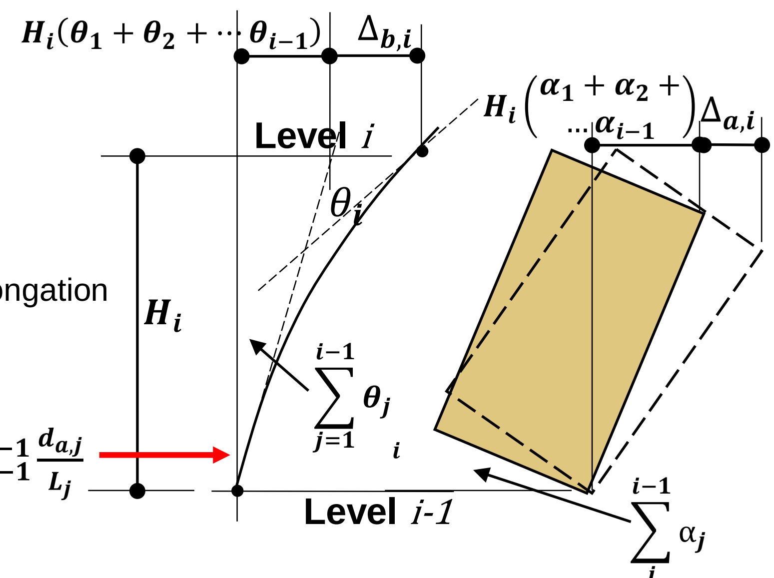
$$\Delta_{b,i} = \frac{V_i H_i^3}{3(EI)_i} + \frac{M_i H_i^2}{2(EI)_i}$$

$$\Delta_{s,i} = \frac{V_i H_i}{L_i B_{v,i}}$$

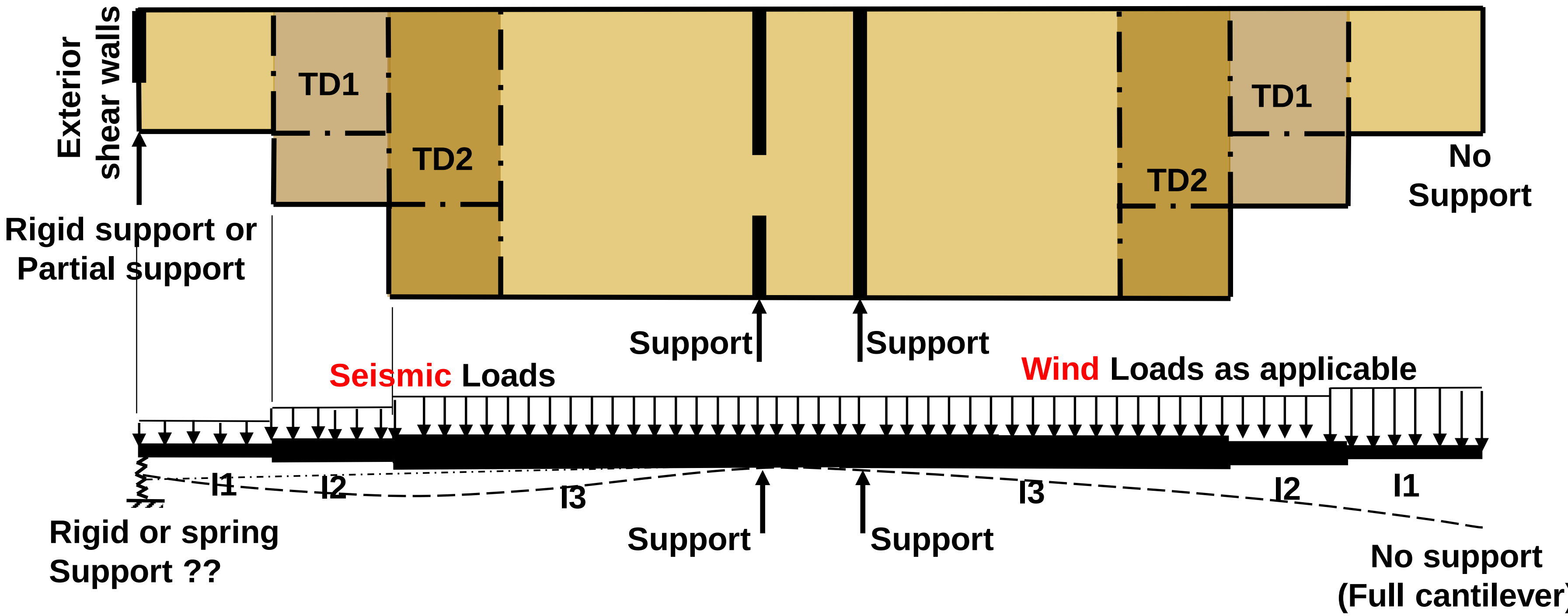
$$\Delta_{n,i} = 0.0025 H_i e_{n,i}$$

$$\Delta_{a,i} = \frac{H_i}{L_i} d_{a,i}$$ (Includes affects of rod elongation and crushing)

$$\Delta_{r,i} = H_i \sum_{j-1}^{i-1} \left(\frac{V_j H_j^2}{2(EI)_j} + \frac{M_j H_j}{(EI)_j} \right) + H_i \sum_{j-1}^{i-1} \frac{d_{a,j}}{L_j}$$

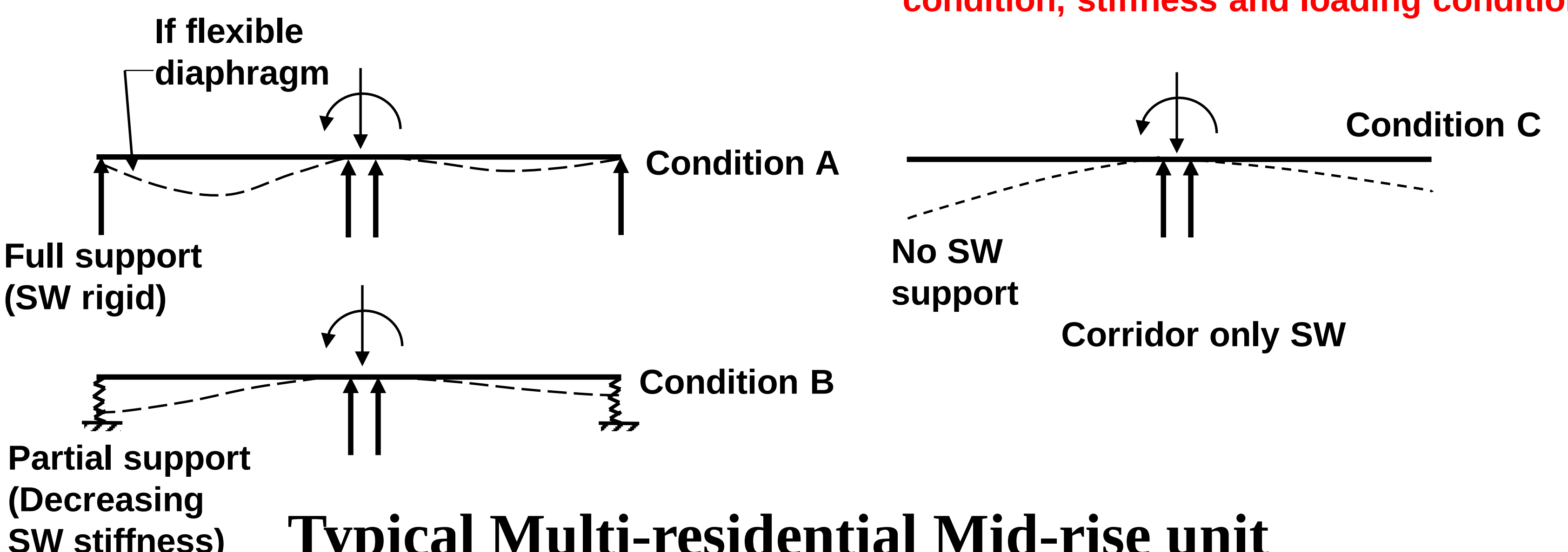


Rotational deflection



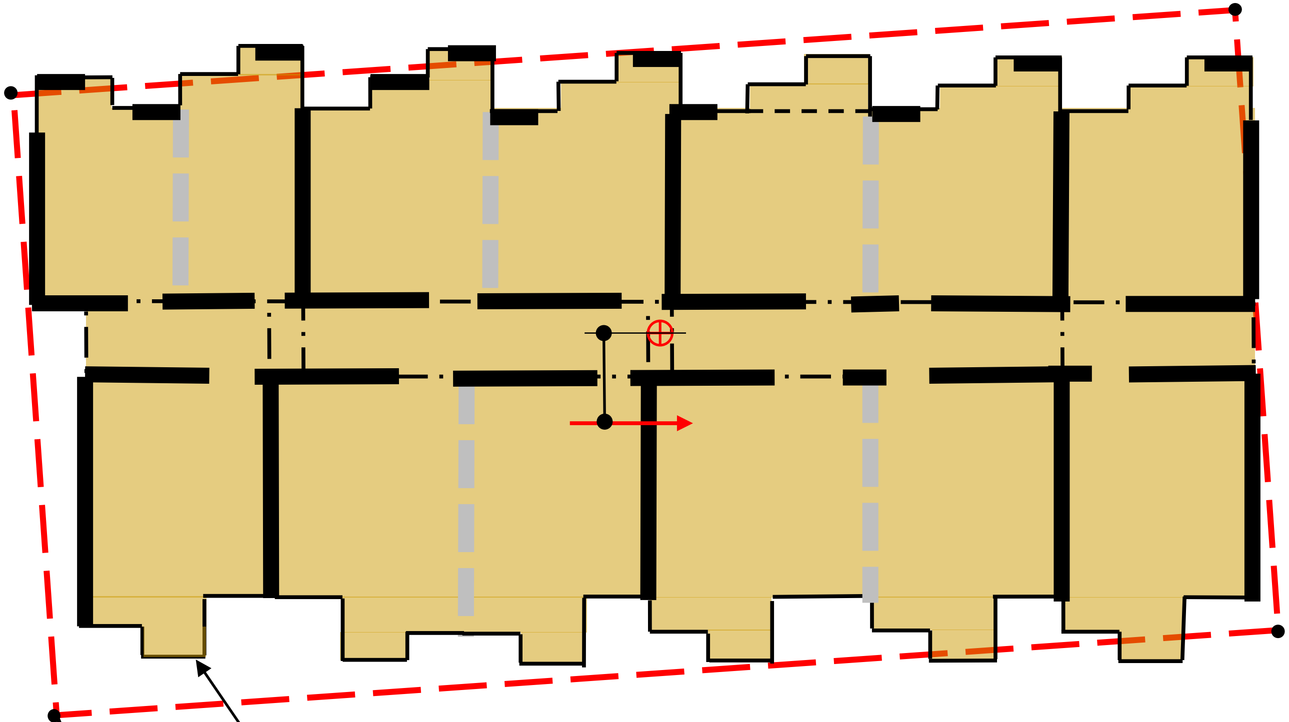
$$\Delta = \frac{5vL^3}{8EAb} + \frac{vL}{4Gt} + 0.188Le_n + \frac{\Sigma(\Delta_C X)}{2b} \quad \text{IBC Eq. 23} - 1$$

Adjust terms of the equation for support condition, stiffness and loading conditions



Typical Multi-residential Mid-rise unit

Longitudinal Loading



No exterior Shear walls ??

Drift by semi-rigid or rigid analysis only

Calculation of drift at corners is required for all open front or cantilever diaphragms (seismic only) including torsion and accidental torsion (Deflection-strength level amplified by Cd.)

In summary:

- **Complex structural layouts require a more detailed analysis than conventional layouts due to the irregularities and discontinuities encountered.**

- **Simple calculation methods and software are available to solve the most difficult problems.**

- **The framing and connections are required to maintain complete load paths and must be fully detailed on the drawings.**

QUESTIONS?

This concludes Our Workshop Presentation on

Advanced Diaphragm Analysis

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