FTAO Analysis for Complex Shear Wall Openings

May 10, 2023

Presented by

Terry Malone, WoodWorks

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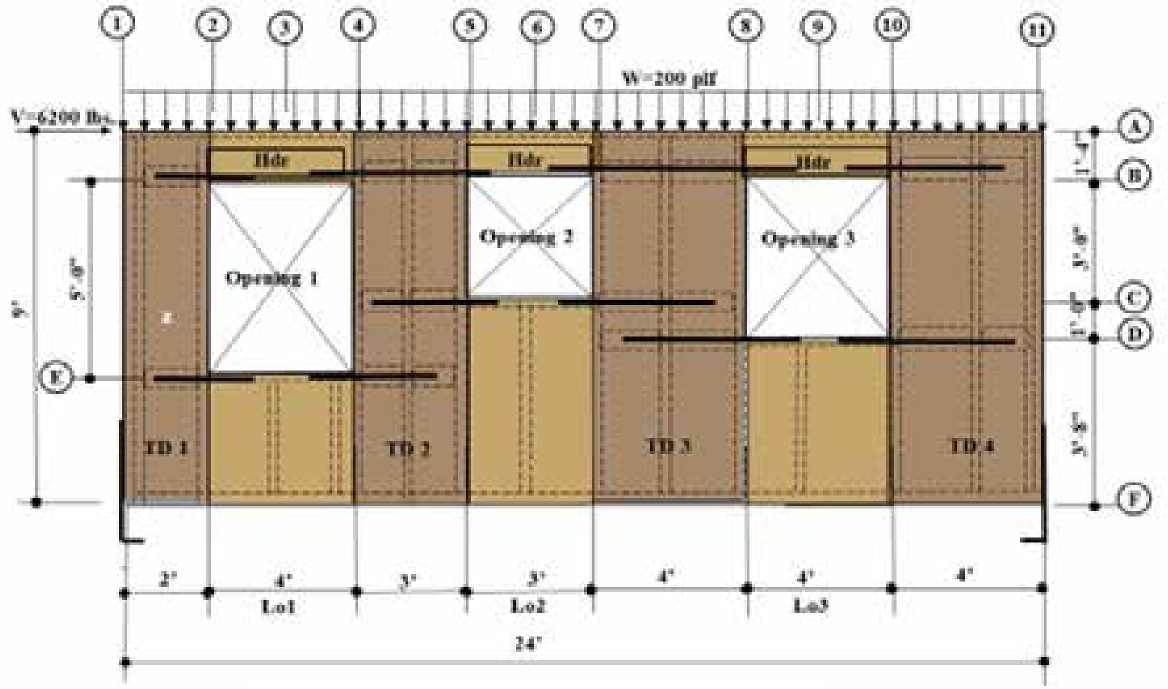
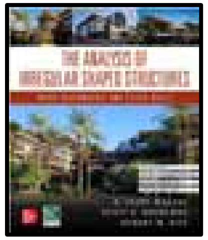


FTAO Analysis with openings of different heights

Content based on
the 2nd Edition, 2022



Terry Malone, PE, SE
Scott Breneman, PhD, PE, SE
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FTAO Shear Wall Analysis Using the Transfer Diaphragm Method

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Course Description

Current methods of Force Transfer Around Openings (FTAO) analysis only allow for openings of the same height in exterior shear walls. However, today's penchant for more openings of different sizes requires a more flexible method that allows for more complex wall layouts. The original method of FTAO analysis was developed by Edward Diekmann in the early 1980s, and other approaches have since been developed, modified and simplified based on his original method and full-scale testing.

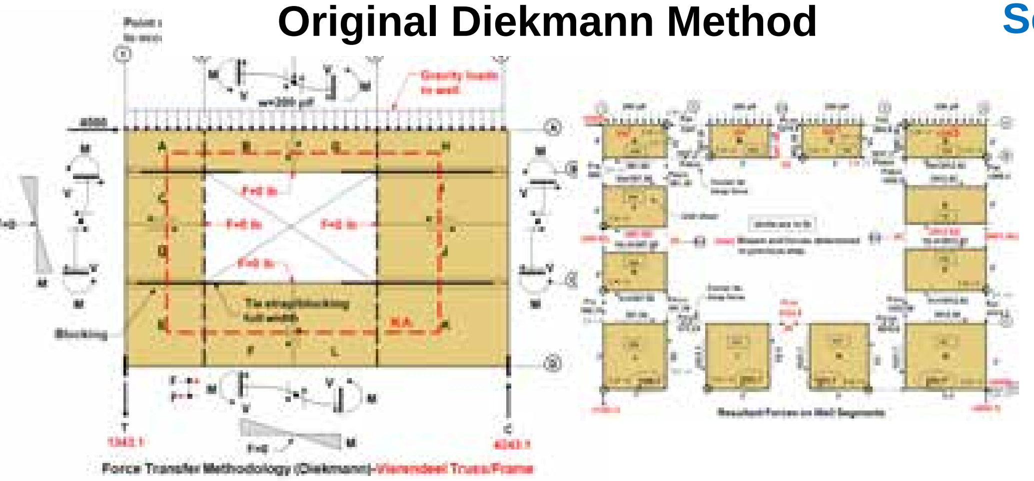
This presentation will demonstrate another modification to FTAO analysis that will allow complex shear wall opening configurations, accommodating the addition of gravity loads, shorter tie straps, and any combination of opening heights using the transfer diaphragm approach.

Learning Objectives

- **Review the history and background to the various methods of FTAO analysis.**
- **Discuss how to use and analyze transfer diaphragms that allow partial length collectors, straps, and openings of different heights.**
- **Provide examples for walls with different opening heights, with and without gravity loads.**
- **Examine stiffness issues regarding the distribution of forces and application of gravity loads through an FTAO wall.**

History of FTAO Methods

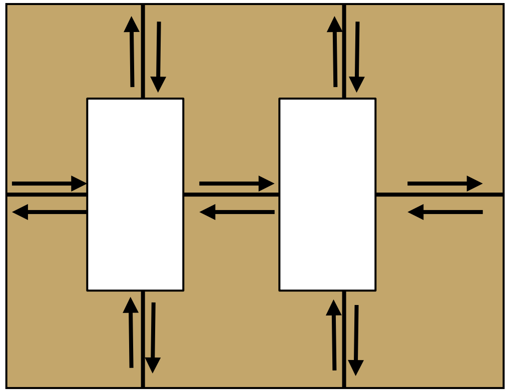
Original Diekmann Method



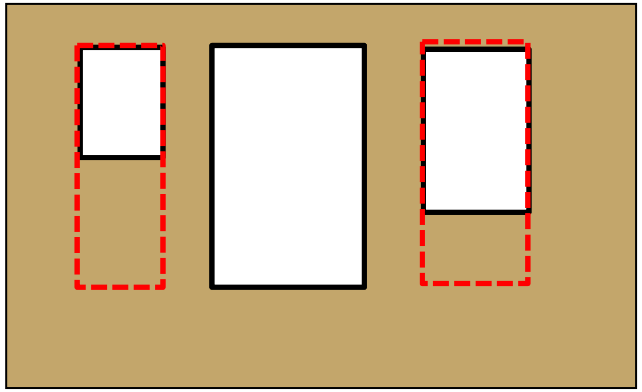
Original concept was a shear wall with a single opening with members of similar stiffness on all sides of the opening that would act as a Vierendeel frame.

- Assumed points of inflection located mid-point of headers, sills and piers.
- Required all sections around the opening to comply with the allowable A.R. or have a similar stiffness.
- Cut free body sections across wall to solve for unknown forces.
- Also Drag Strut Analogy and Cantilever Beam Analogy

Thompson Method/SEAOC Seismic Design Manual, Vol. 2



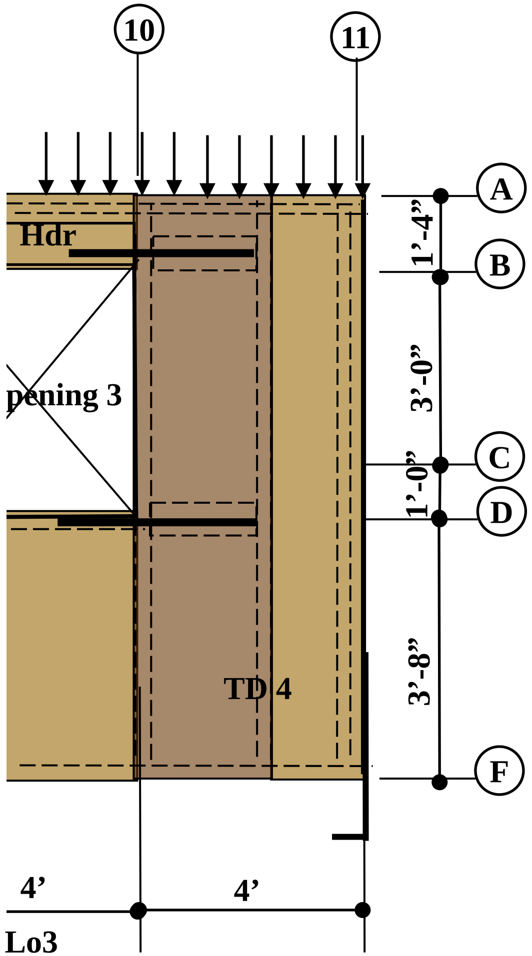
APA Simplified Diekmann FTAO Method



Both use Diekmann method with some variations/modifications.

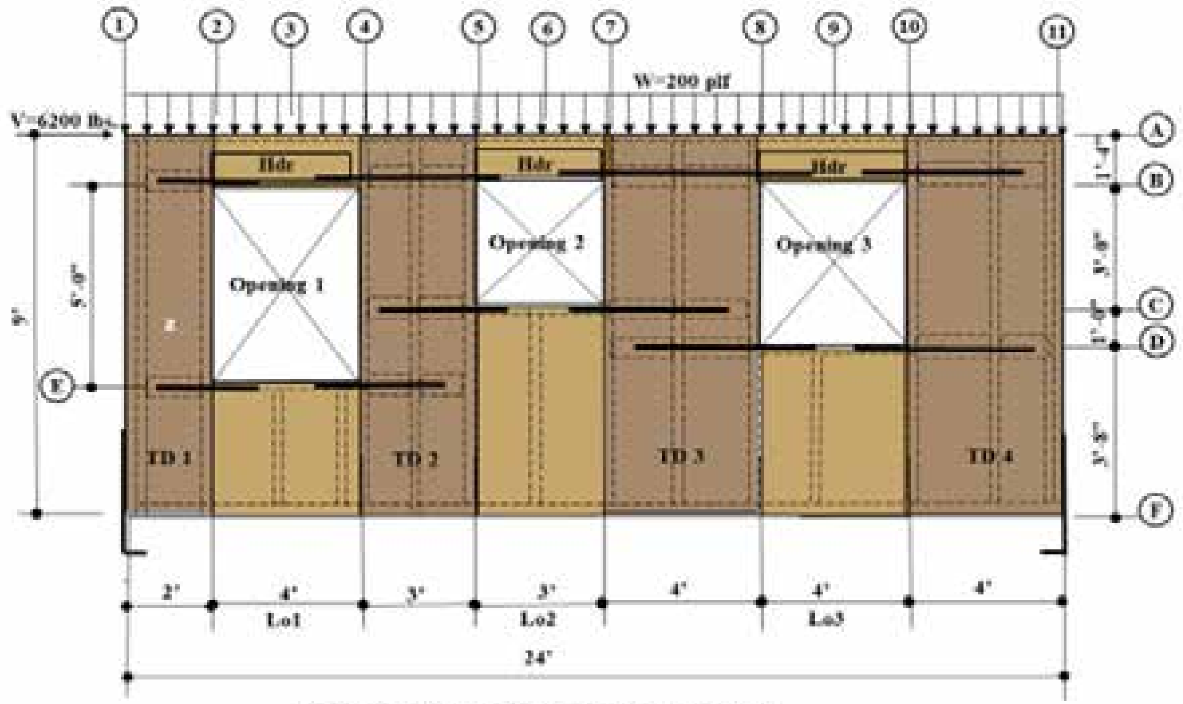
Both calculate inflection points based on relative stiffness of adjacent pier sections.

Thompson Method/SEAOC	APA Simplified Diekmann FTAO Method
Assumes horizontal unit shears at the sides of the opening are uniform.	Assume the vertical unit shears above and below the opening are equal.
Unknown forces are determined by free body diagrams in static equilibrium.	Used test results to simplify and verify design methodology. Corner forces at the openings determined by unit shears.
Gravity loads are not applied but mentioned as optional.	Gravity loads are not applied.
Shows all openings are of equal height but does not mention treatment of openings of unequal height.	Requires openings of equal height for simplicity, but notes that methodology does not require that assumption.



1st Edition, 2012

- Short tie straps
- Gravity loads
- Single opening



FTAO Shear With Uniform Load
Multiple Openings of Different Heights

2nd Edition, 2022- Further developed method

- Short tie straps
- Gravity loads
- Multiple openings
- Tops of openings at any height
- Openings any height combination
- Stacked openings

History of FTAO Transfer Diaphragm Method

Continuous Tie Strap Misconceptions

Full length straps
are not necessary

2008 SDPWS Section 4.3.5.2 (4)

Collectors for shear transfer shall be provided through the full length of the wall.

2021 SDPWS Section 4.3.2.2 (5)

Collectors for transfer of shear forces between the diaphragms and shear wall shall not be less than the full length of the FTAO shear wall. (Wall top plate)

Causes of confusion:

- Unclear definition of term “Collector”.
- Early photos showing continuous tie straps installed.
- Method of using shorter straps not provided or discussed (except in 1st edition of book).

Anchor location


JOINT RESEARCH REPORT

Evaluation of Force Transfer Around Openings – Experimental and Analytical Studies

APA Wall tests – Form M410

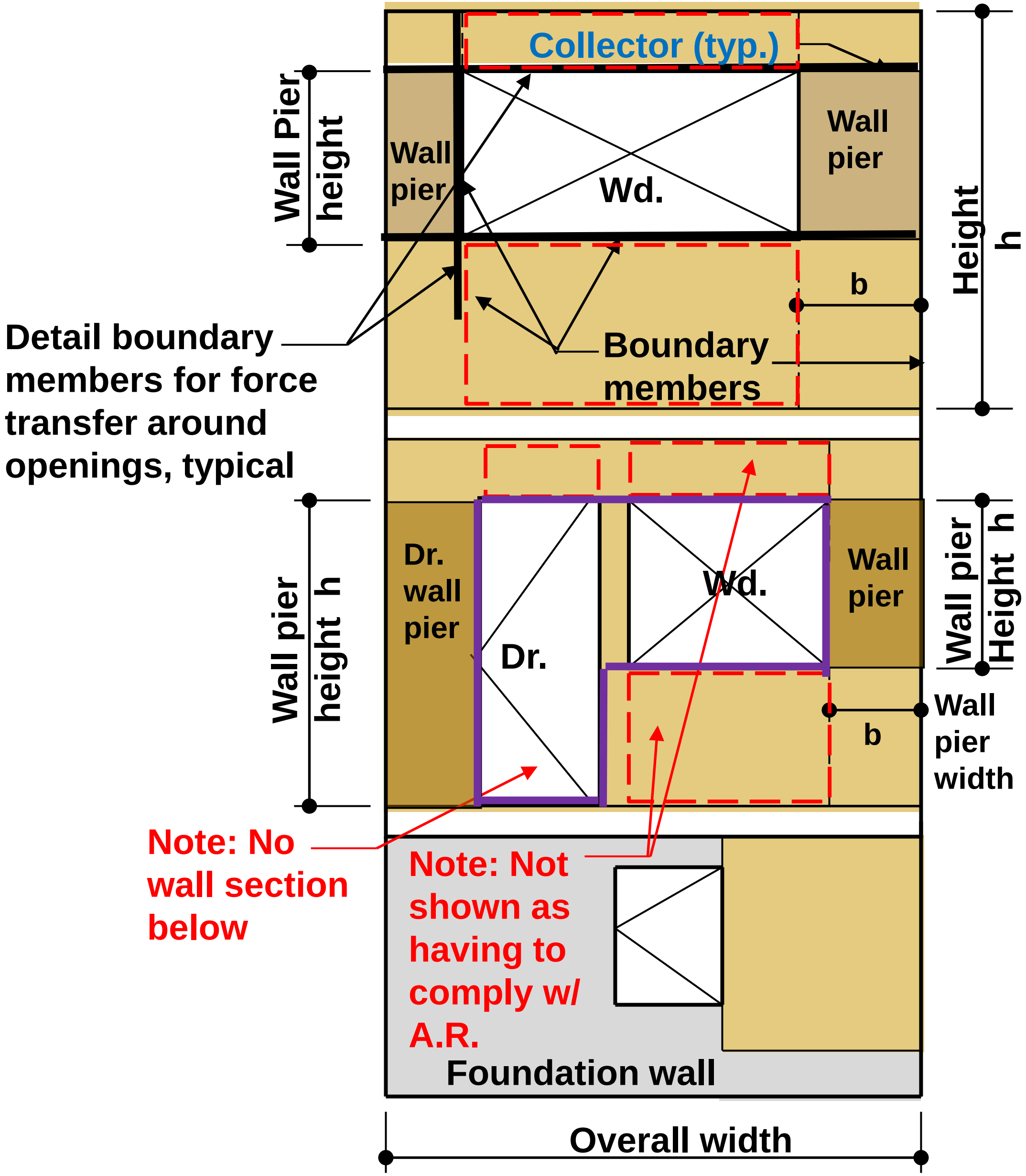
Partial length straps/anchors

Connected to 1st bay blocking only

APA Wall tests 8 and 9 – M410

Wall 8 – IMG_1297
Wall 9 – IMG_1667

Photo credit APA: The engineered Wood Association



AWC SDPWS Figure 4E (Sim)
(b) Force Transfer Around Opening

2021 SDPWS Section 4.3.2.2 -Limitations

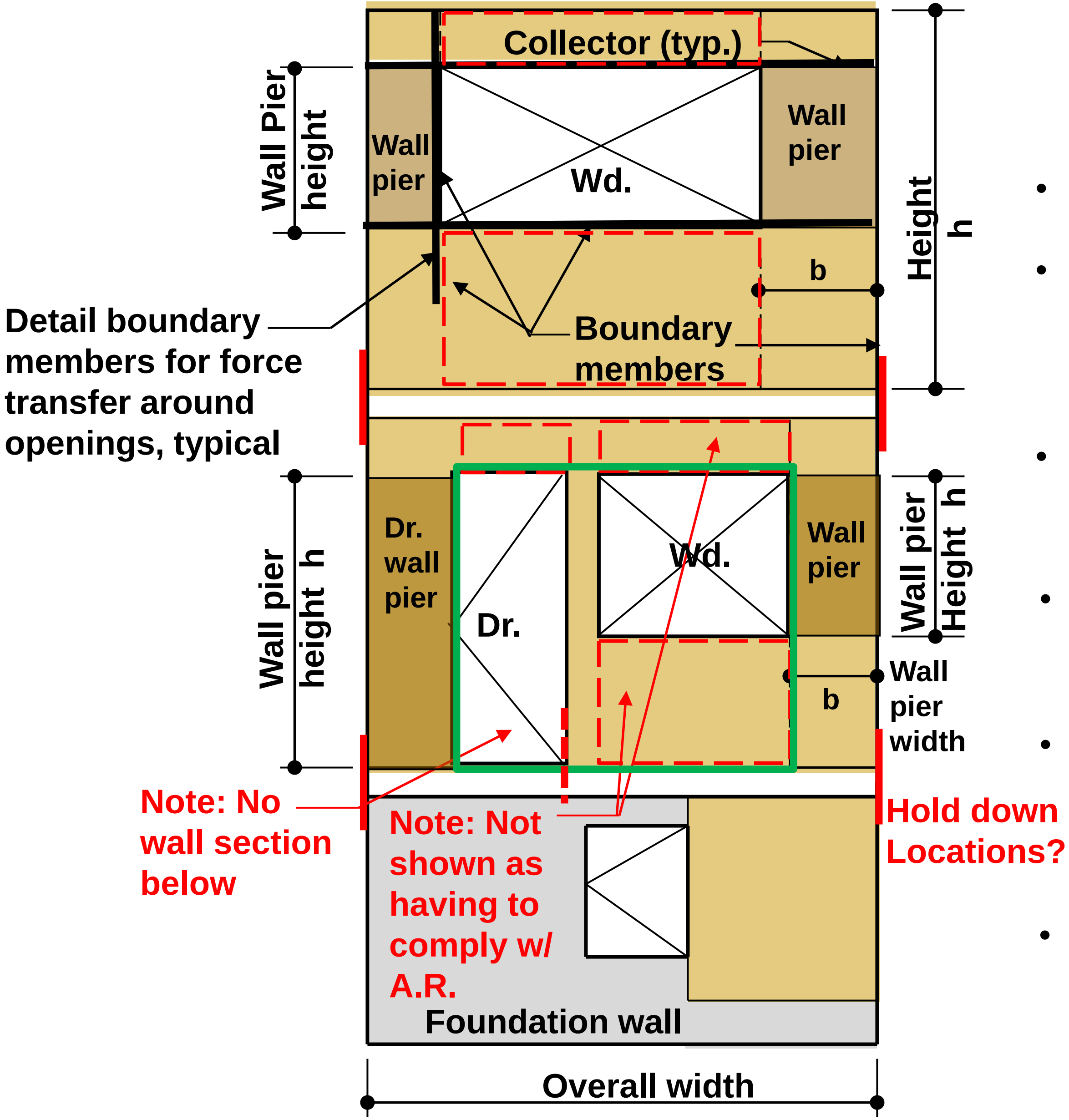
Based on Rational analysis:

- Minimum pier width=2'-0".
- Where a horizontal offset occurs, portions on each side of the offset shall be considered as separate FTAO walls.
- Collectors for shear transfer shall be provided through the full length of the wall.
- A full height pier section shall be located at each end of the wall.
- The aspect ratio limitations of Table 4.3.3 shall apply to the the pier sections on each side of the openings
- All sections with A.R.>2:1 required application of new Aspect Ratio Factor (WSP) = 1.25-0.125h/bs

ATC 7, Diekmann, FPInnovations
If the sections above, below or on each side of the opening do not meet code aspect ratio limits it should be ignored, not stiff enough to transfer forces across the opening.

So, what is the opening?

Allowable Shear Wall Aspect Ratios For FTAO Shear Walls



AWC SDPWS Figure 4E (Sim)

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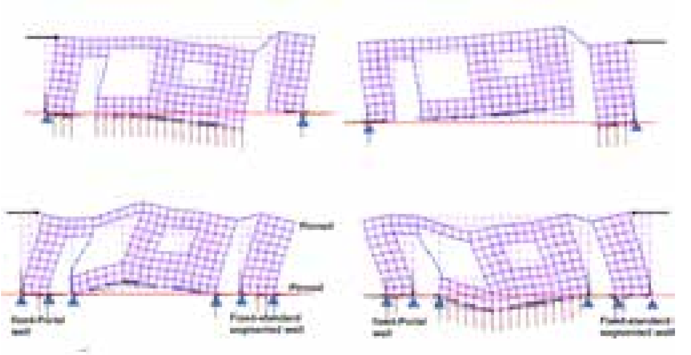
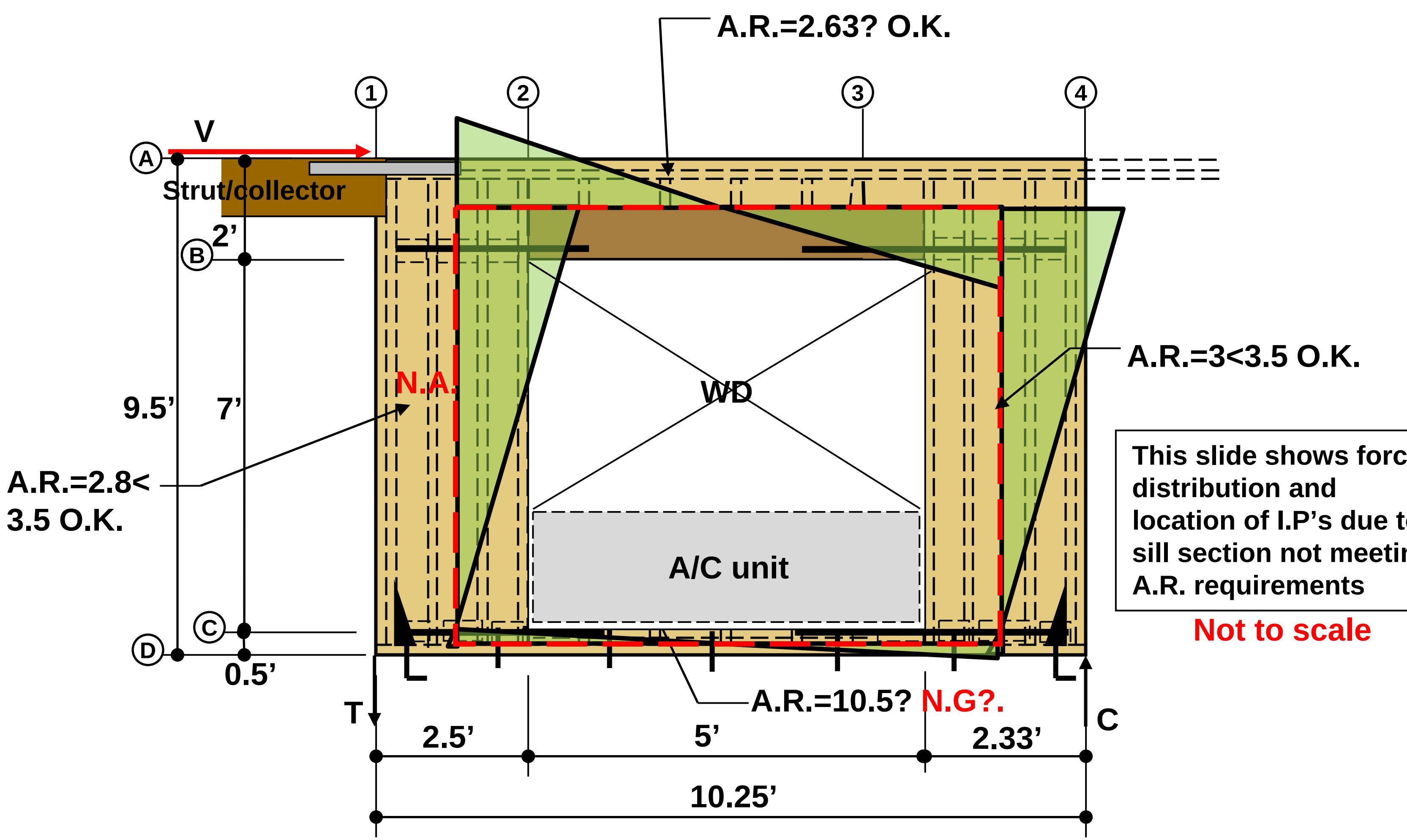


So, what is the opening?

Allowable Shear Wall Aspect Ratios For FTAO Shear Walls

Force Transfer Based on stiffness (FEA analysis)

Example results – Single opening with shallow sill.

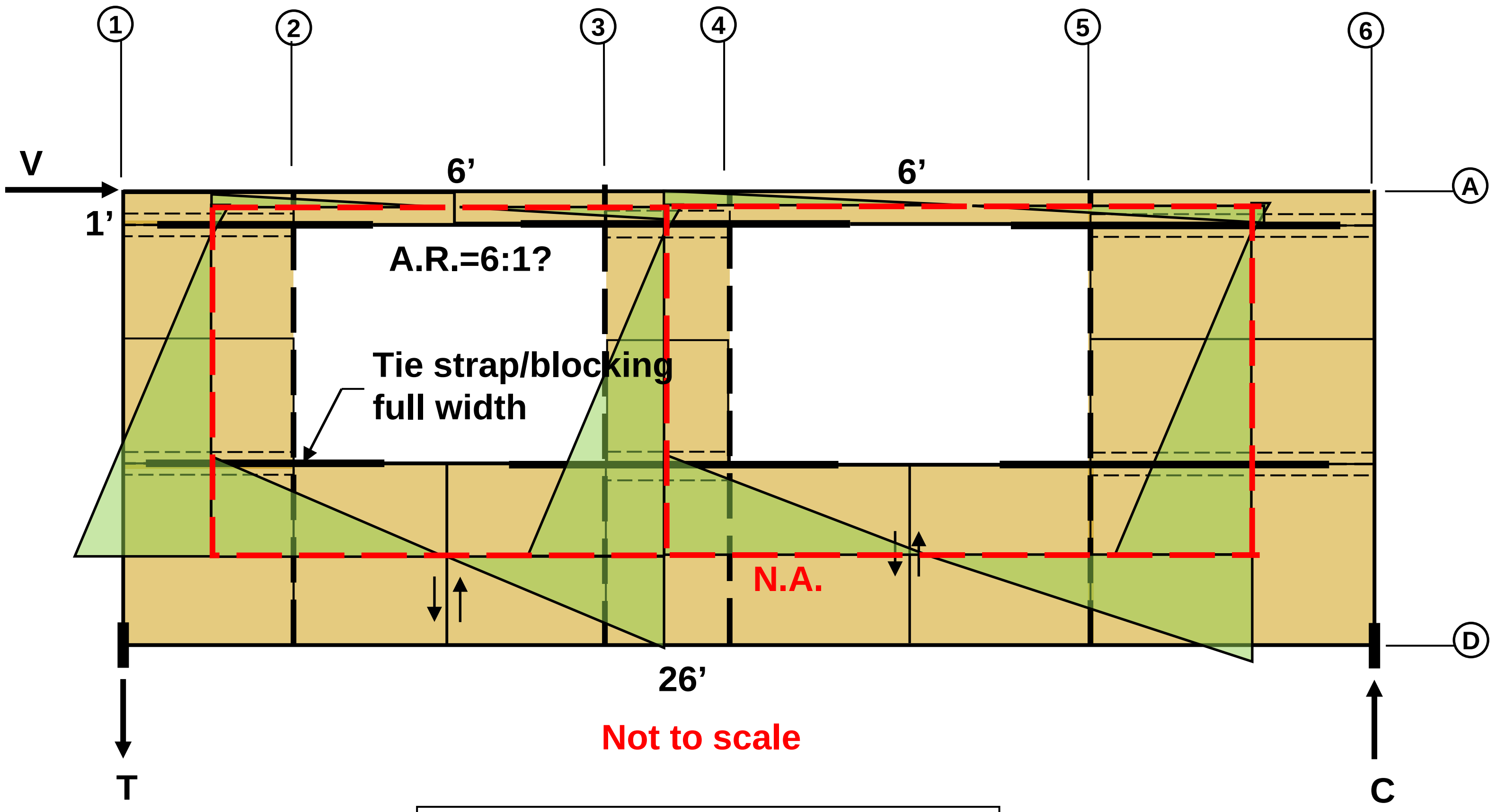


This slide shows force distribution and location of I.P's due to sill section not meeting A.R. requirements

Not to scale

Force Transfer Based on stiffness

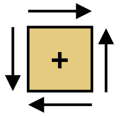
Example results – double opening with shallow headers



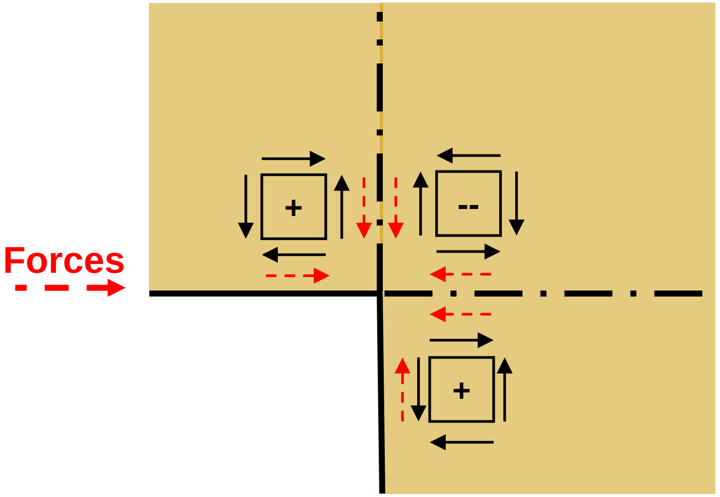
This slide shows force distribution and location of I.P's if header section not meeting A/R requirements

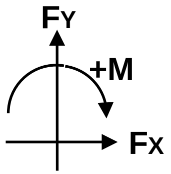
The Visual Shear Transfer Method

How to visually show the distribution of shears through the diagraphms and shear walls

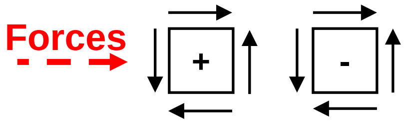


Sheathing element symbol for 1 ft x 1 ft square piece of sheathing in static equilibrium (typ.)



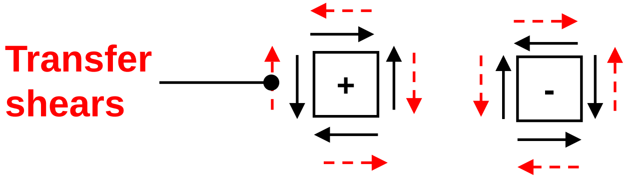


Positive Direction



Transverse Direction (shown)

Shears Applied to Sheathing Elements



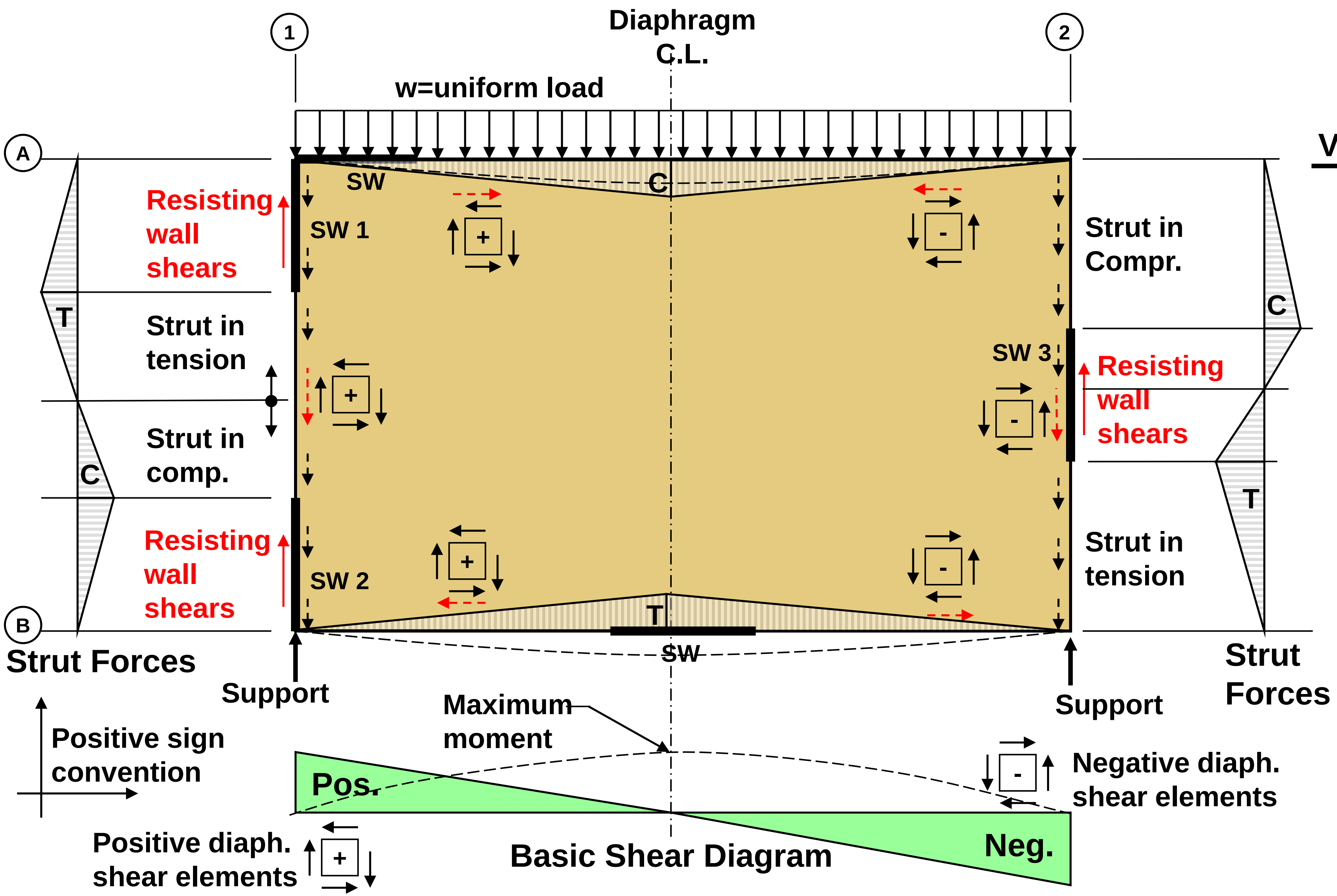
Unit shear acting on sheathing element (plf)

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

Shears Transferred Into Boundary Elements

Shear Wall Sign Convention

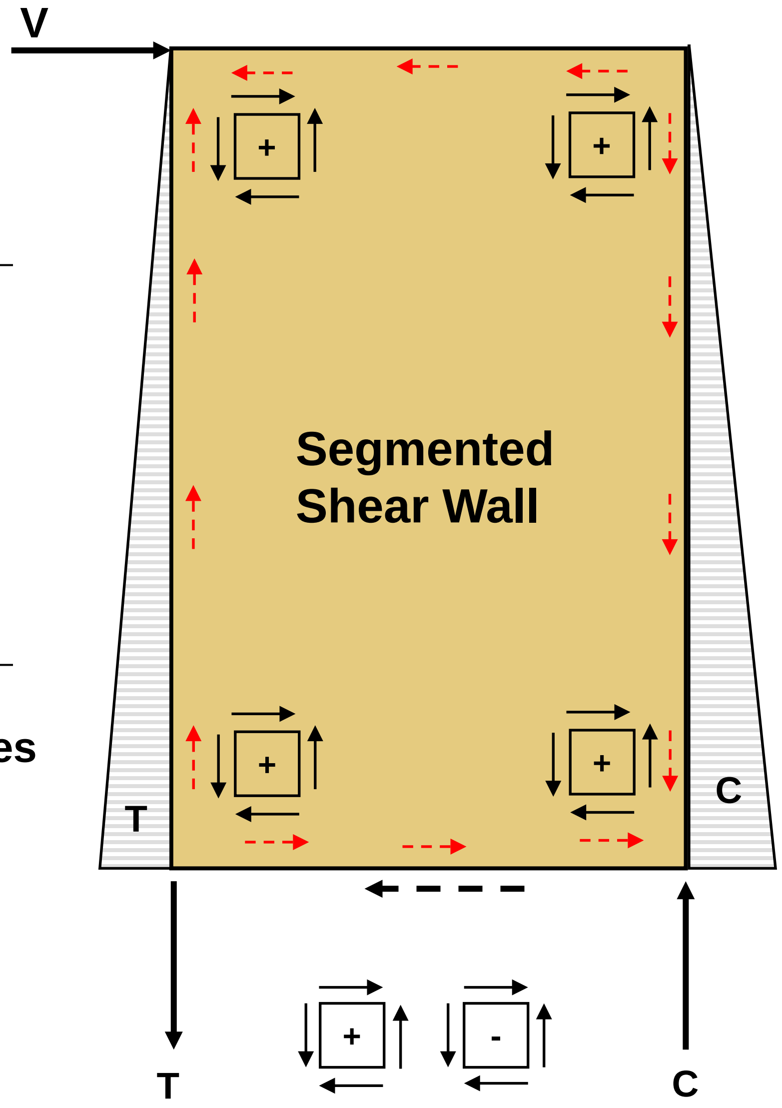
Positive shear is in direction of applied force



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).

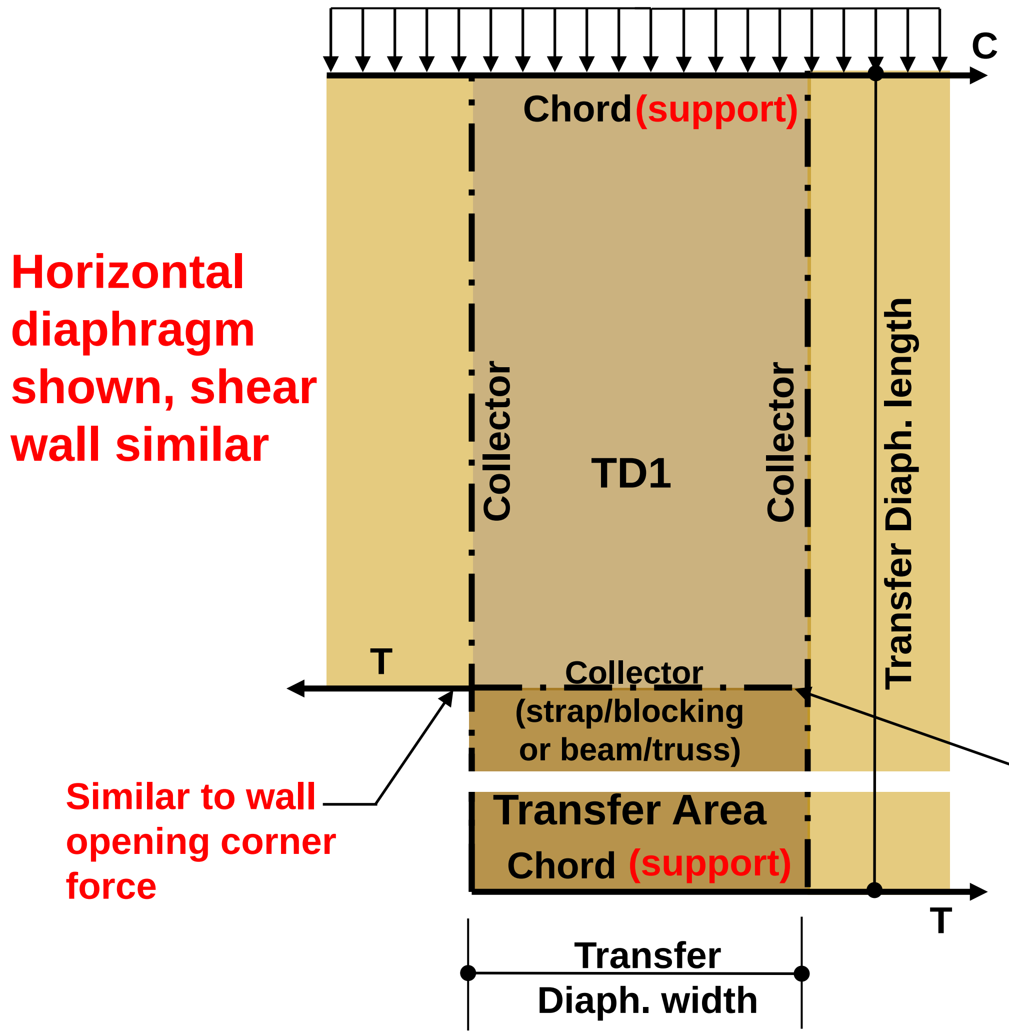
Shear Distribution Into a Simple Diaphragm

The Visual Shear Transfer Method



Shear Distribution Into a Simple SW

Introduction to Transfer Diaphragms



Transfer Diaphragm

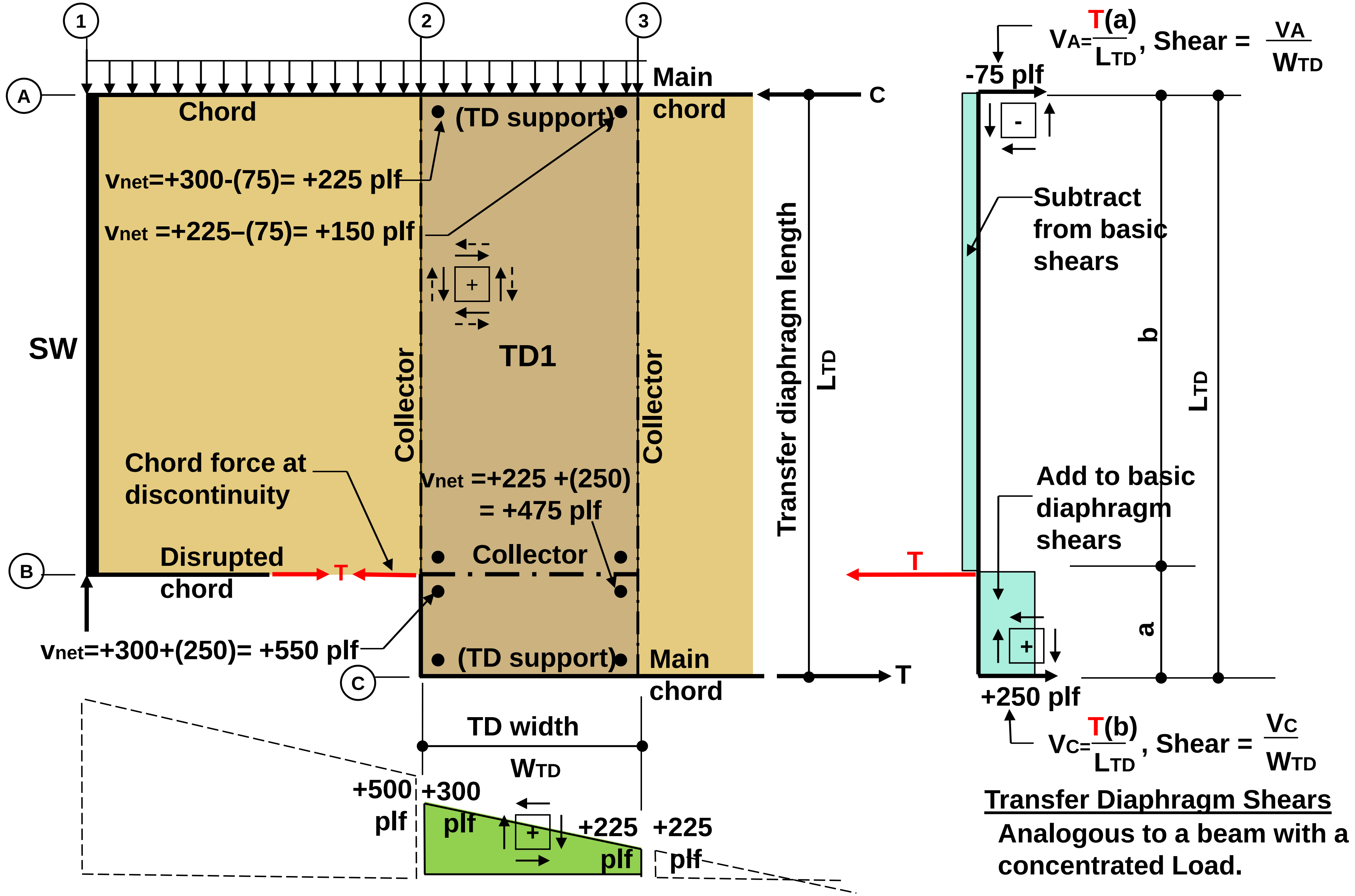
- Sub-diaphragm-don't confuse w/ sub-diaphragms supporting conc./masonry walls
- Transfers local forces out to the top and bottom plates of the shear wall. (Based on method, ASCE 7 Section 1.4 and SDPWS 4.1.1)
- Maximum TD Aspect Ratio=4:1 (roof or floor diaphragms) (Similar to main diaph.)- Max. A.R. for SW TDs = 6.5:1
- Framing members, blocking, and connections shall extend into a diaphragm or shear wall a sufficient distance to develop the force transferred into the diaphragm or shear wall. (SDPWS 4.2.1)

What does this mean?

Collector Length?-My rule of thumb:

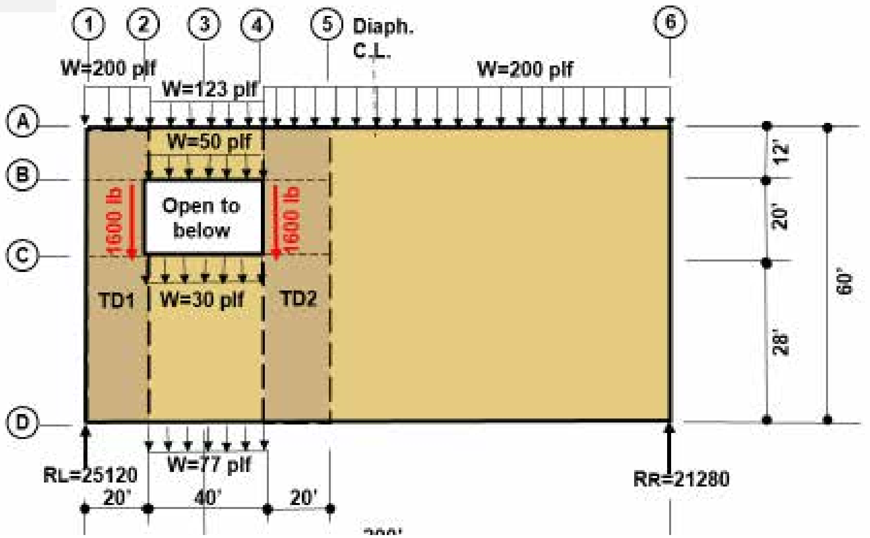
- Check length by dividing discontinuous force by the nailing capacity (other issues need to be considered)
- Length=full width of transfer the diaphragm, set by A.R.
- Increase TD width if shears are too high in transfer area

Method of Analysis-Method by Edward F. Diekmann

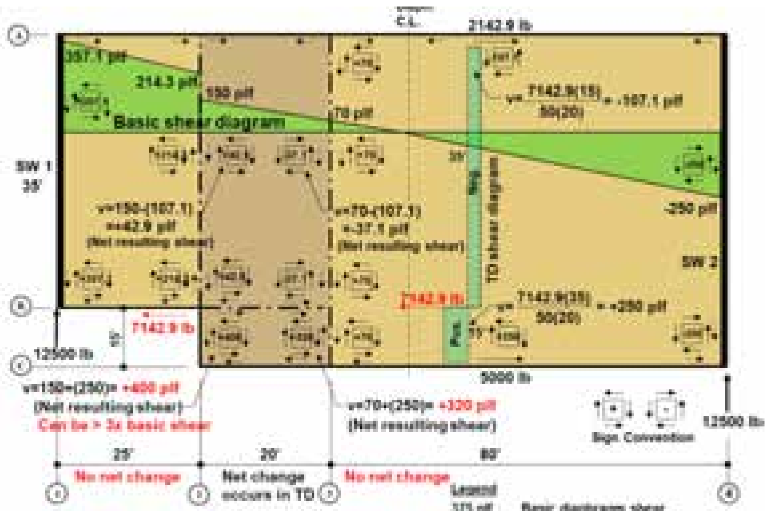


Basic Shear Diagram at transfer diaphragm

Transfer Diaphragm Method Uses



Diaphragms with Openings



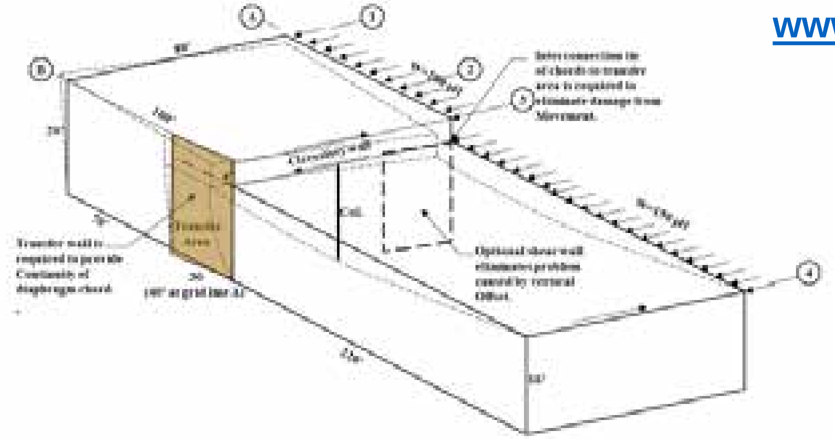
Horizontally Offset Diaphragms

Woodworks/Solution Papers

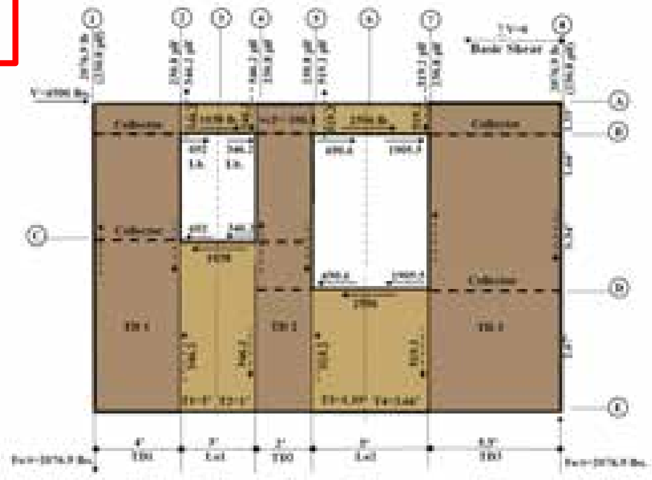
The Analysis of Irregular Shaped Diaphragms

(for complete Transfer Diaphragm example)

www.woodworks.org



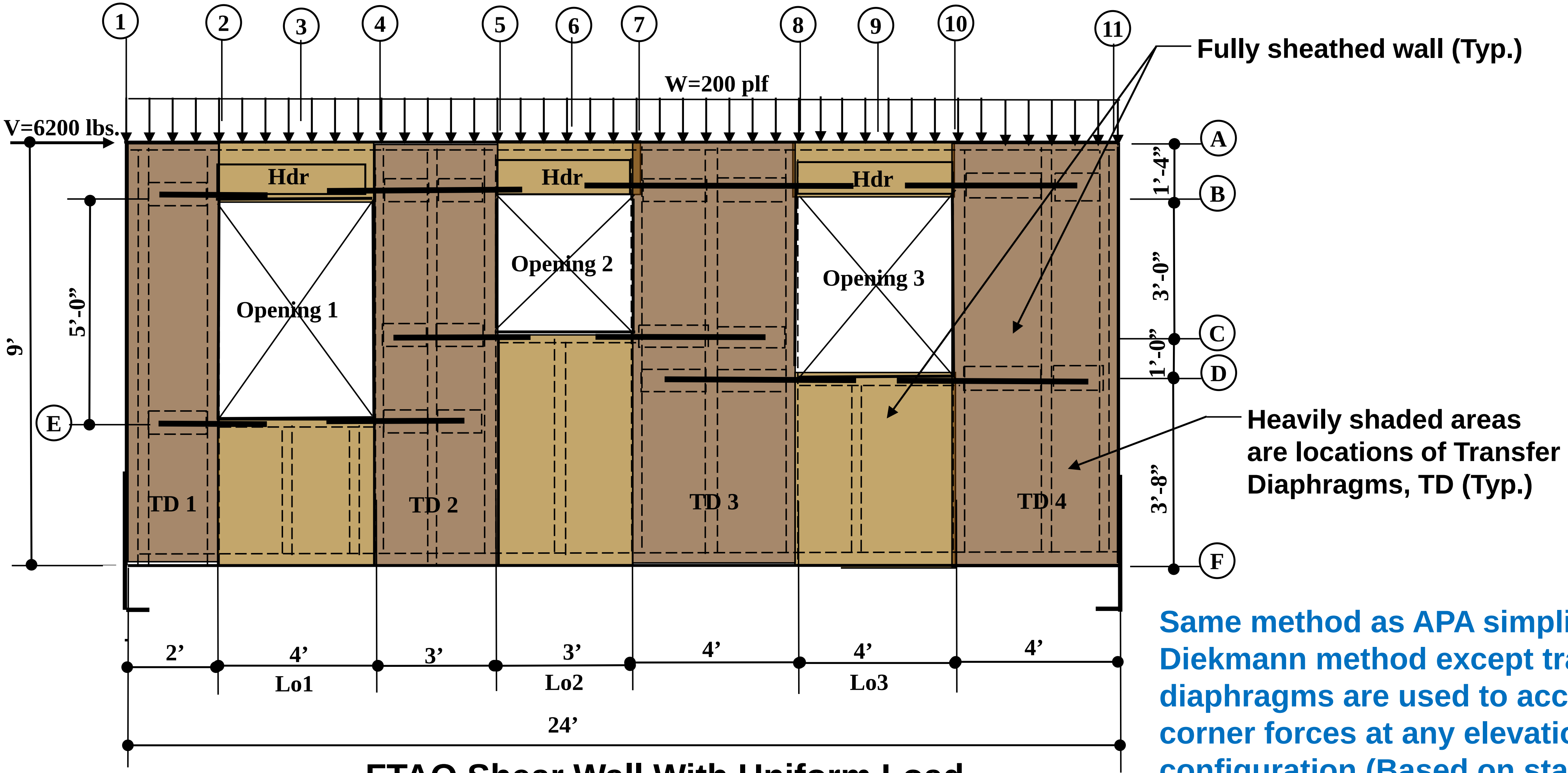
Vertically Offset Diaphragms



Complex FTAO Shear Walls

Introduction to FTAO SWs-Transfer Diaphragm Method

Reference Chapter 10, Section 10.3



FTAO Shear Wall With Uniform Load
Multiple Openings of Different Heights (shown)

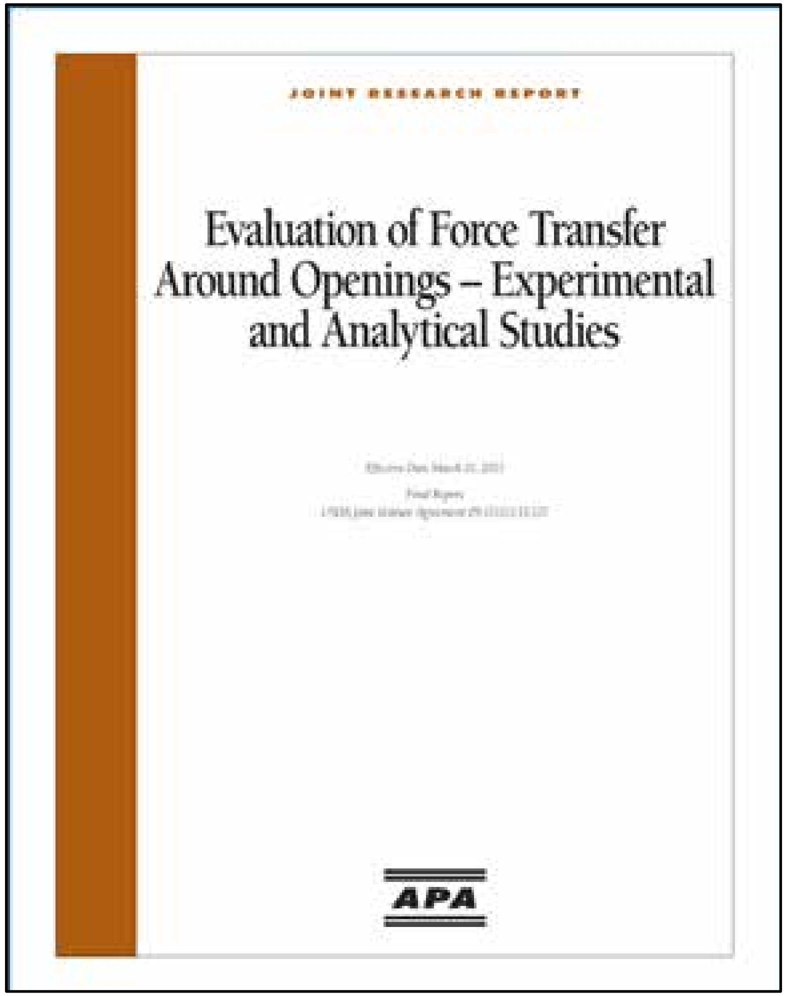
Same method as APA simplified Diekmann method except transfer diaphragms are used to accommodate corner forces at any elevation or any configuration (Based on statics)

Verification of TD Method vs. APA/Diekmann Method

Using APA Example/Spreadsheet

Method compared to Full Scale Tests

Latest Technical Note
T555

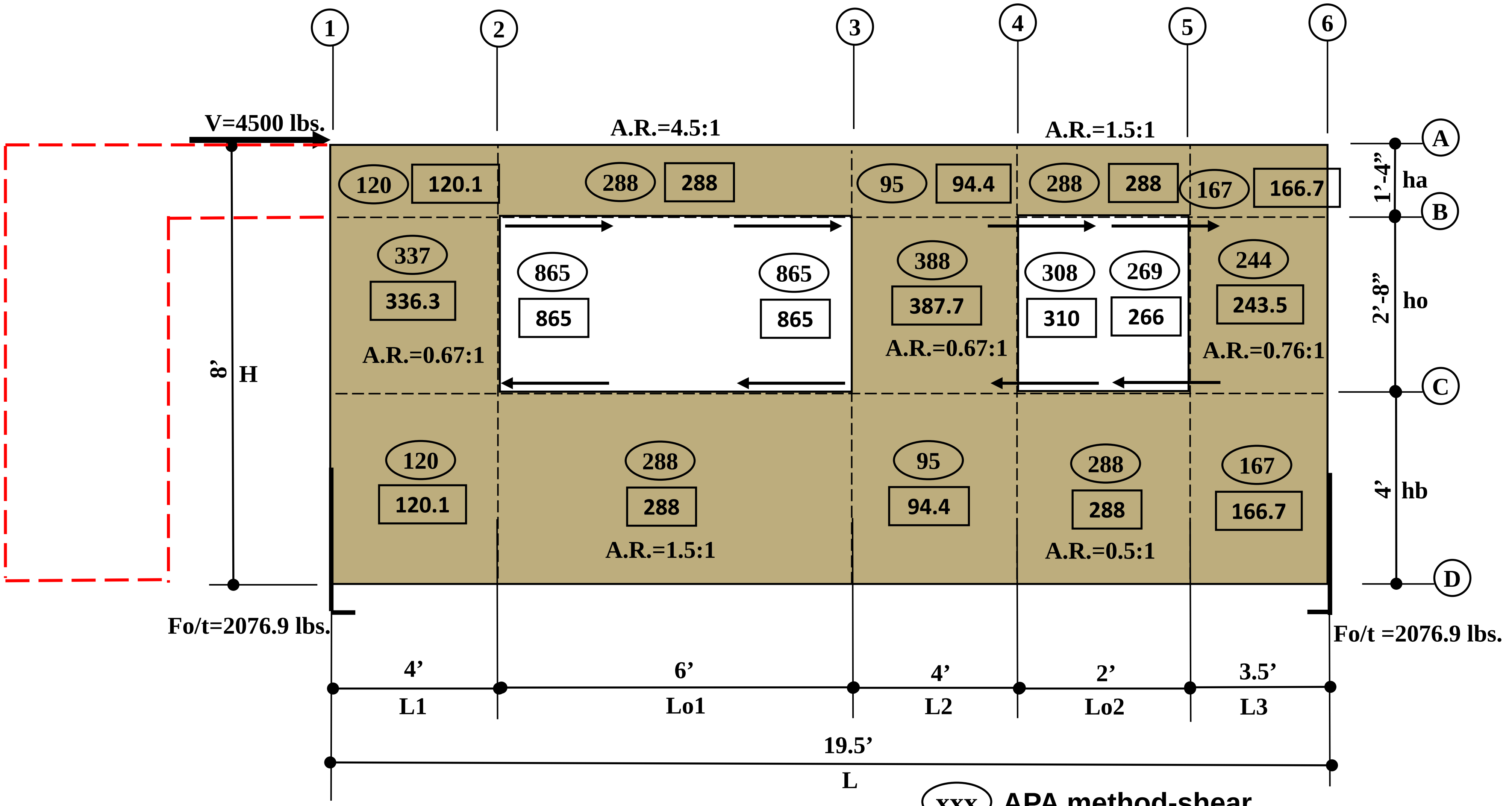


Full Scale Tests
Form M410

Comparison and Verification of TD Method vs. APA/Diekmann Method

Using APA Example and Spreadsheet

Note: APA design example shows door section but does not include it.



xxx APA method-shear

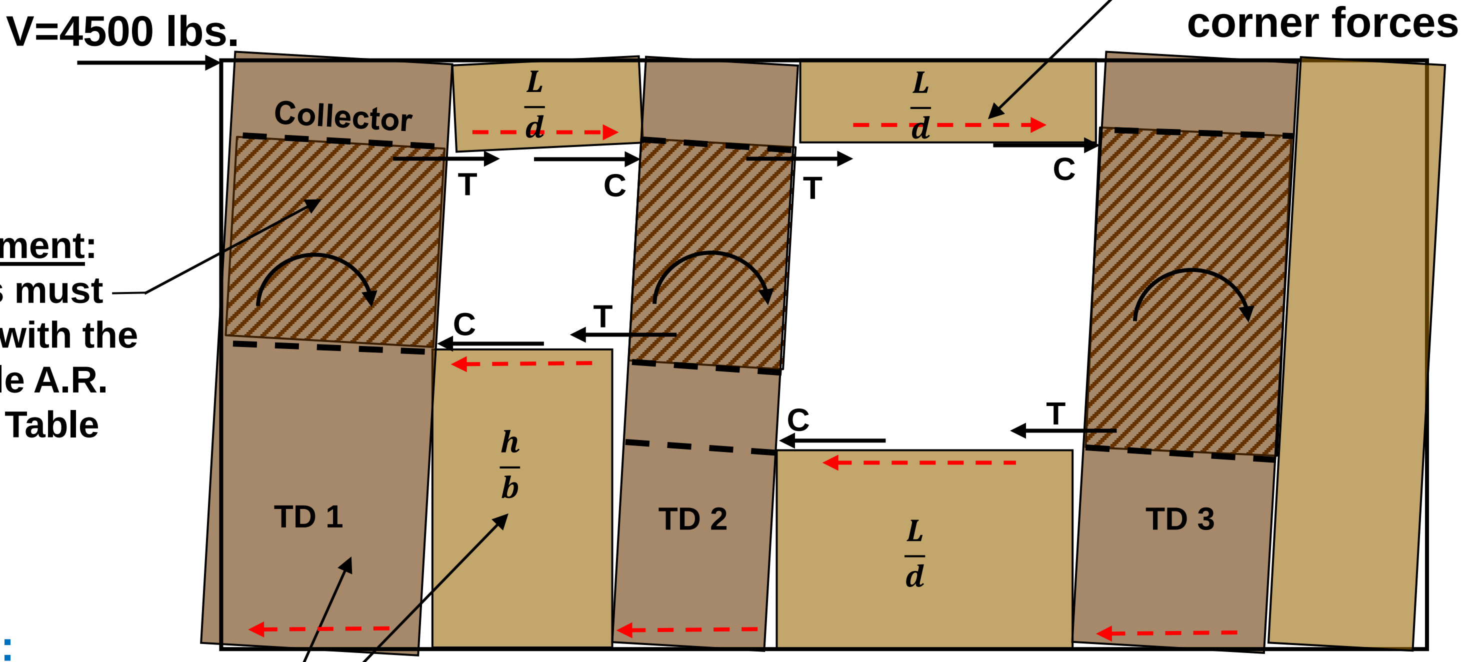
xxx TD method-shear

APA Technical Note T555

APA Full Scale Tests M410

FTAO Transfer Diaphragm Concept

Direction of forces above opening and corner forces



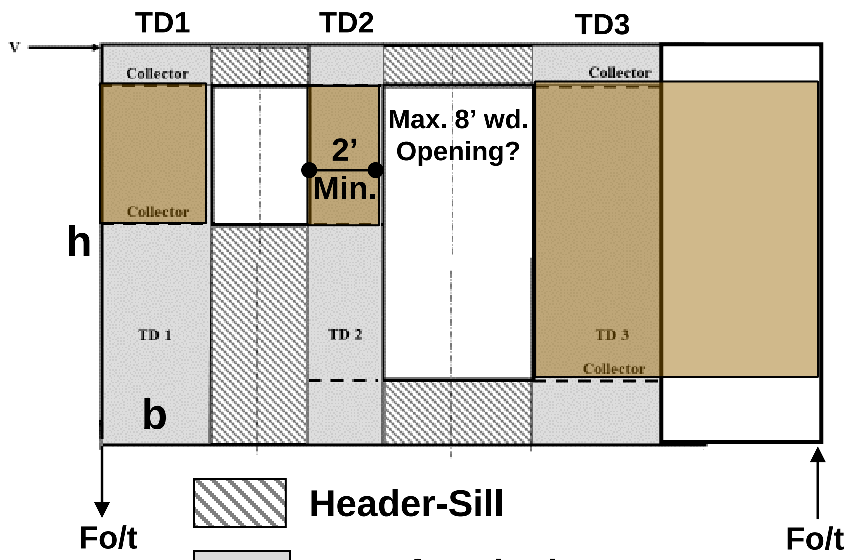
<u>Requirement</u>:
All piers must comply with the allowable A.R. SDPWS Table 4.3.3.

<u>Suggest</u>:

<u>2nd assumption:</u>
Headers, sills, and Transfer Diaphragms should comply with the maximum <u>tested</u> A.R., A.R.=6.5:1 or less, if possible. See limitations next Figure

- <u>1st assumption:</u> Transfer diaphragms act like rigid segmented shear wall sections rotating against and away from header/sill sections causing tension and compression forces at the corners of the openings.
- The calculated corner forces are the discontinuous forces that are applied to the transfer diaphragms.
- These discontinuous forces change the unit shears within the transfer diaphragm sections which must be combined with the wall basic unit shear to get a net shear.
- Aspect ratios for headers, sills shall be determined by the aspect ratio that produces the largest A.R. (h/b or L/d).

Header & Sill A.R. Limitations



Maximum Hdr./Sill Length

A.R	3.5:1	4:1	4.5:1	5:1	5.5:1	6:1
<u>dheader</u>						
1'	3.5'	4'	4.5'	5'	5.5'	6'
1.33'	4.67'	5.33'	6'	6.67'	7.33'	8'
2'	7'	8'	9'	10'	11'	12'

Minimum Transfer Diaphragm Widths

A.R	3.5:1	4:1	4.5:1	5:1	5.5:1	6:1
h=12' b min.	3.5'	3'	2.67'	2.33'	2.25'	2'
h=10 b min.	2.83'	2.5'	2.25'	2'	-----	-----
h=9' b min.	2.5'	2.25'	2'	-----	-----	-----
h=8' b min.	2.25'	2'	-----	-----	-----	-----

Author preferred ratio. If higher, check shears.

APA Test Walls, Form M410

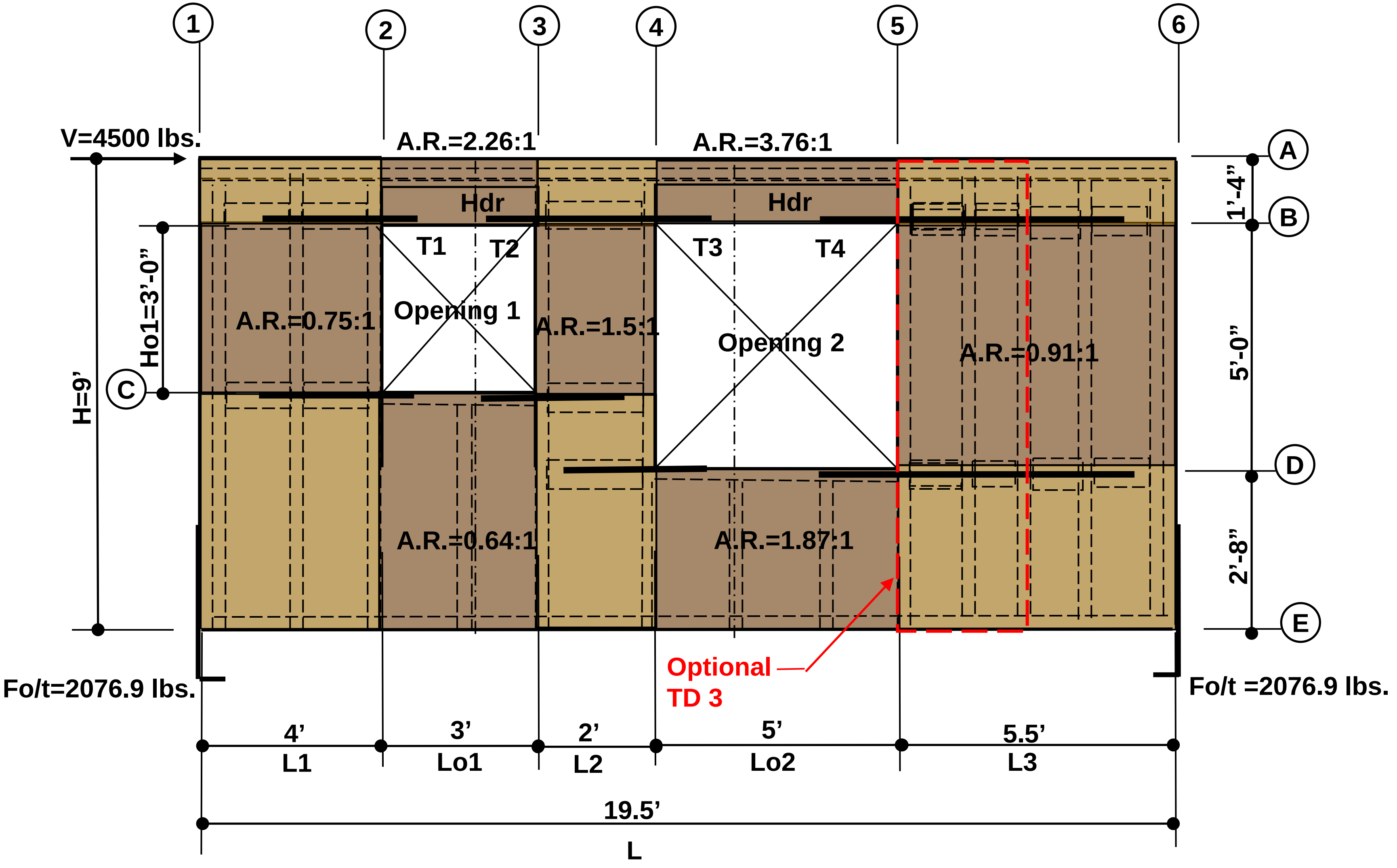
Wall height = 8'
Maximum opening width = 7.5'
Minimum pier width=1.5', A.R.=2.67:1
Typical header depth = 1.167', A.R. = 6.43:1
Minimum sill depth = 1.83, A.R. = 4.1:1

APA notes that a header or sill section with an A.R.= 6.5:1 is stiff enough to work in an FTAO shear wall, <u>based on tests</u>.

1. h=wall height
2. Minimum width pier 2'-0" per SDPWS Section 4.3.2.2 (2)
3. APA-Minimum depth header/sill 1'-0" , if less, cannot use FTAO method

Not inclusive of Portal Frames

Example 1-Force Transfer Around Opening (FTAO) Transfer Diaphragm Method -Without Dead loads



Note: All loads used in these examples have been factored for the load combination used.

Steps:

1. Calculate O/T forces
2. Determine A.R. of piers, hdrs., and sill sections

H=height of wall

L=length of wall

L1=length of pier 1

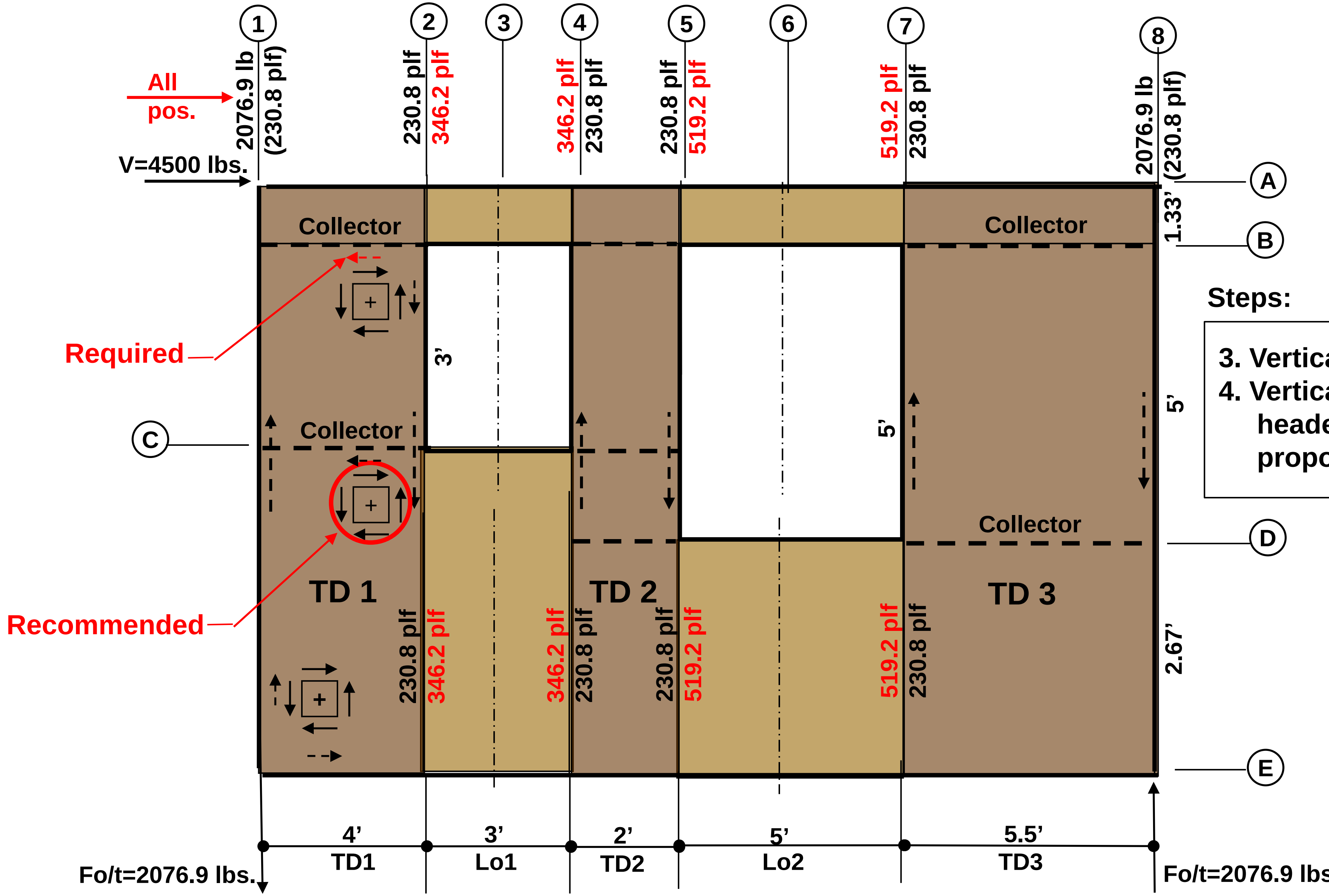
Lo1=length of opening 1

Ho1=height of opening 1

A.R.=aspect ratio of section

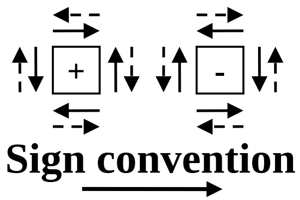
TD=transfer diaphragm

T1=tributary width of opening 1 at left side



Steps:

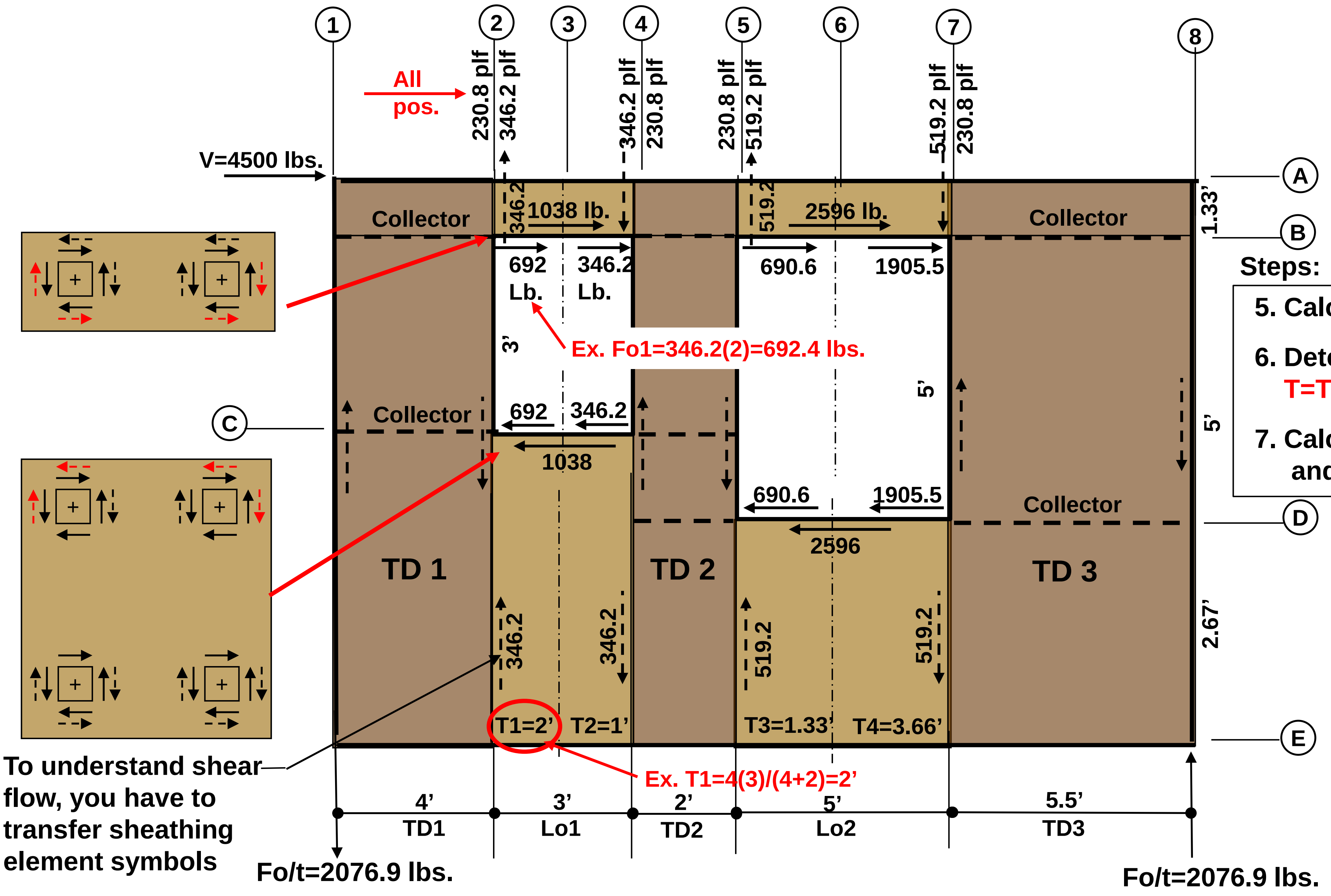
3. Vertical unit shears, v = Fot/H
4. Vertical shear is distributed to header and sill sections in proportional to their depths.



Sign convention

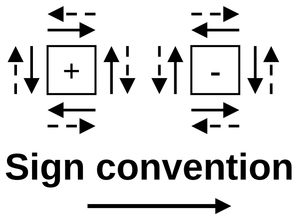
Positive is in direction of applied force

Calculate Vertical Shear Forces

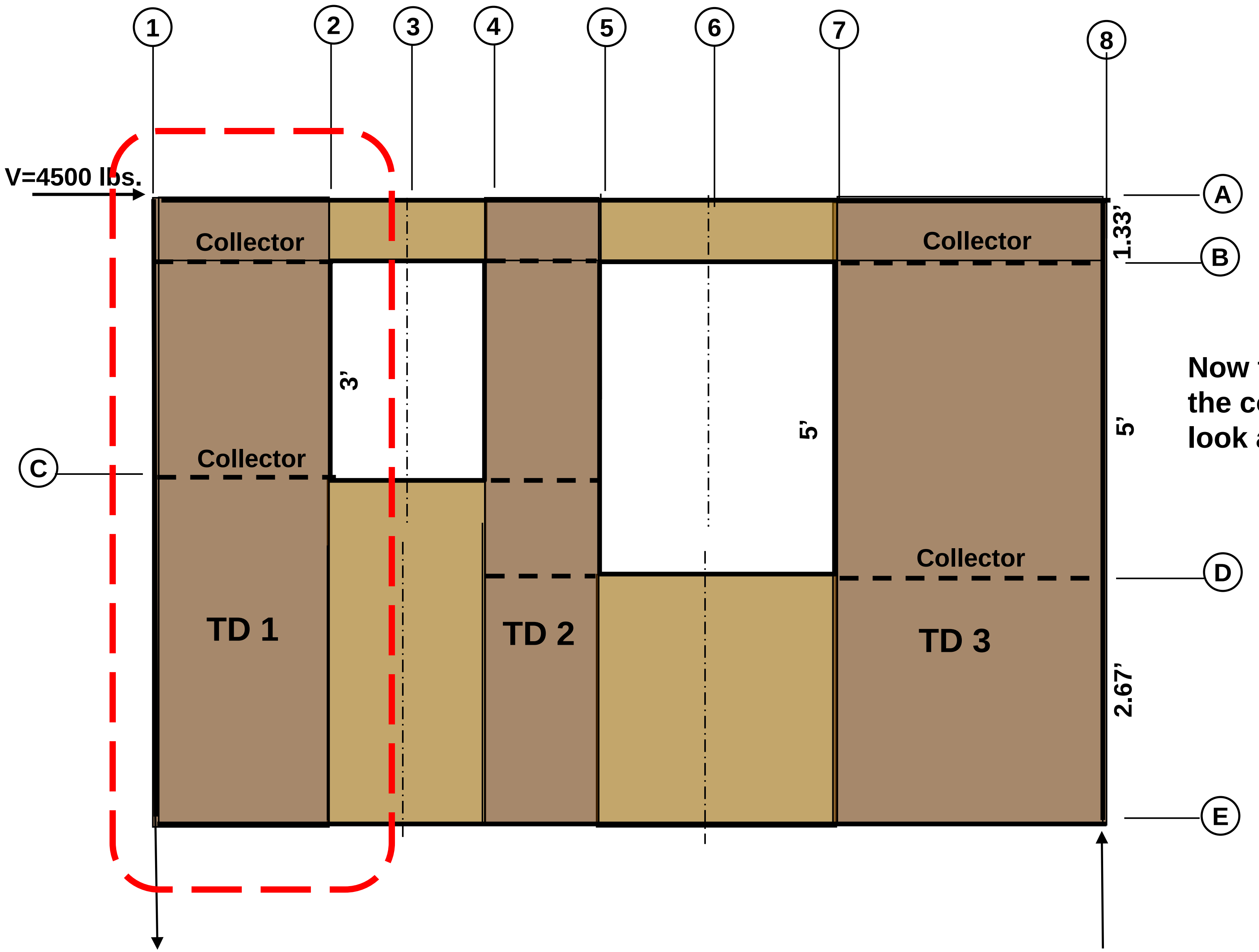


Steps:

5. Calculate forces to hdrs. F=v(Lo1)
6. Determine trib. widths at open's
   T=TD1(Lo1)/(TD1+TD2)
7. Calculate trib. forces at hdrs. and sills (corner forces). Fo1=v(T1)

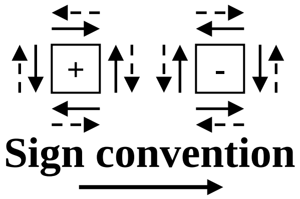


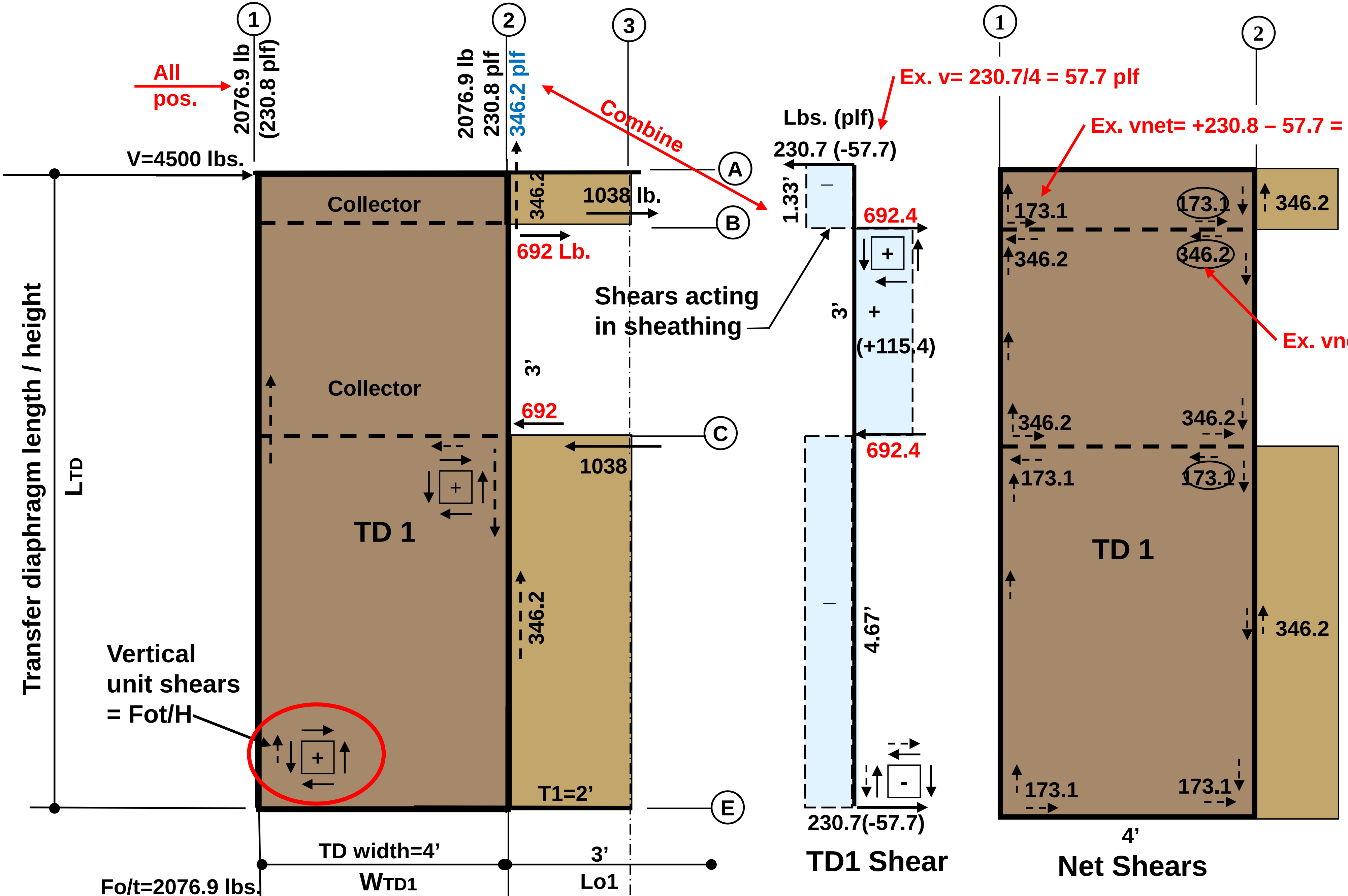
Calculate Tributary Widths, and Corner Forces



Now that we have determined the corner forces, let's take a look at the transfer diaphragms

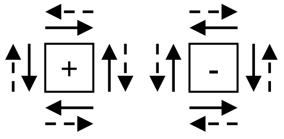
Analyze Transfer Diaphragm 1





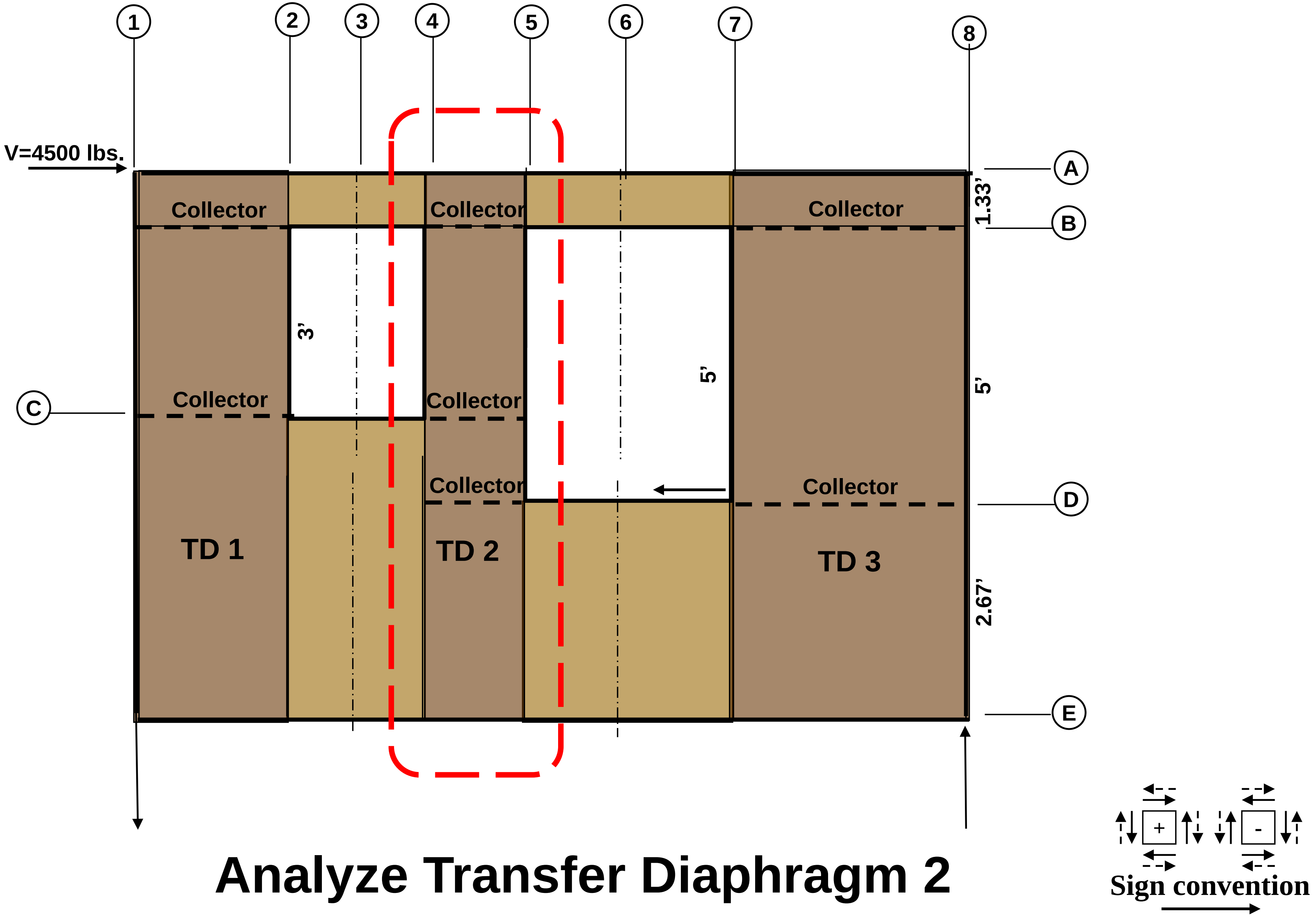
Steps:

8. Calculate TD shears caused by corner forces
9. Determine net shears in TD

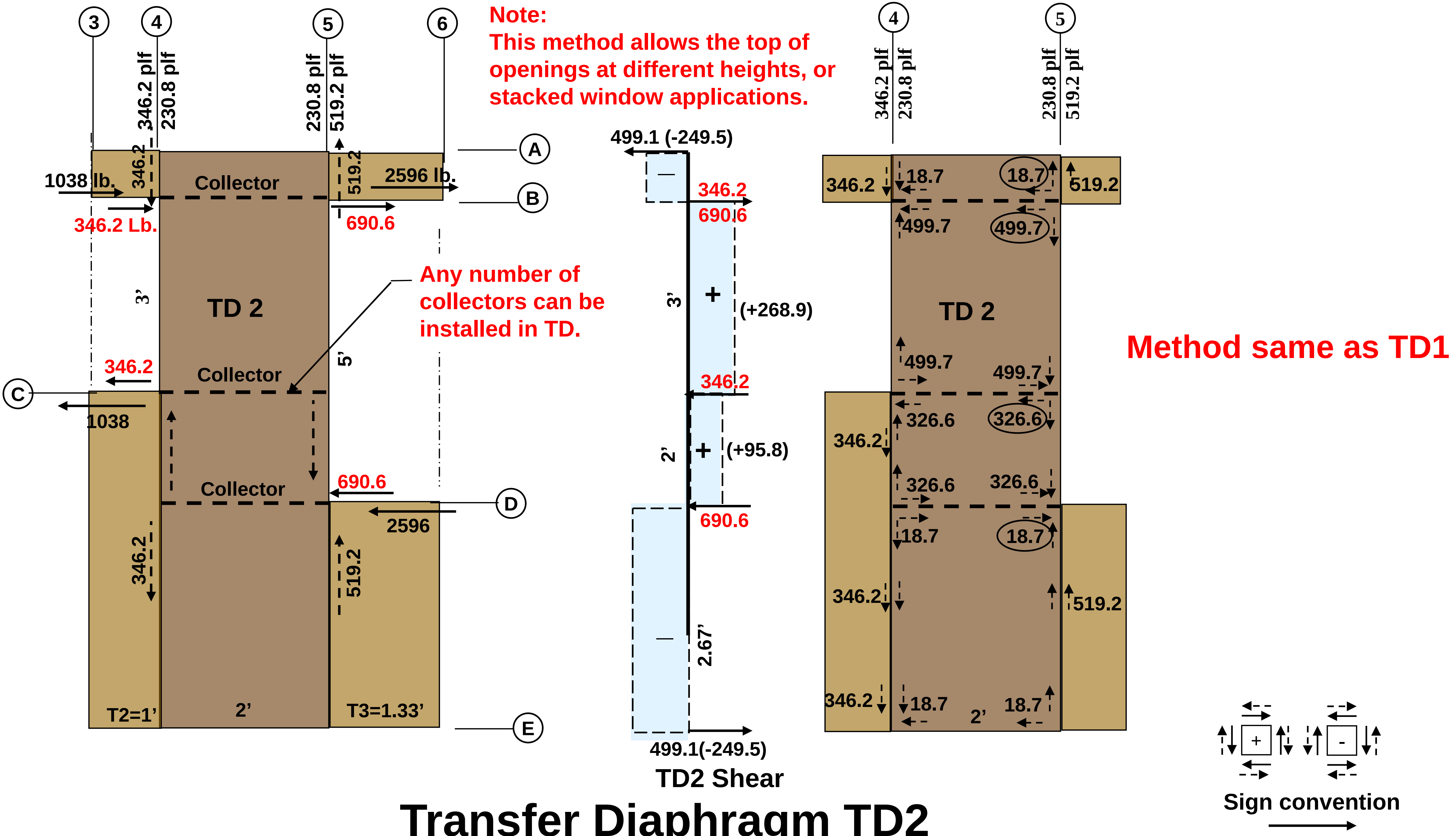


Sign convention

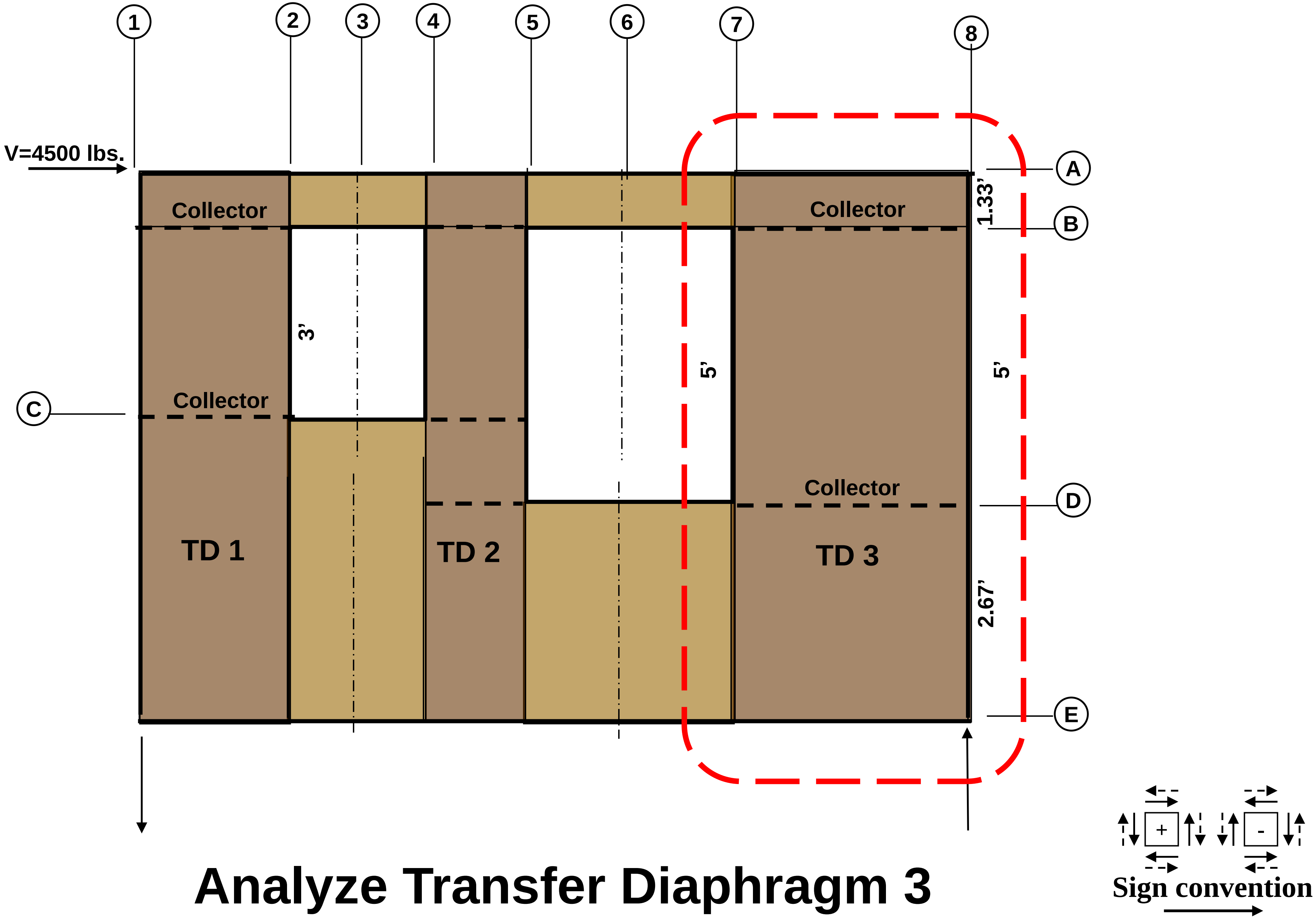
Transfer Diaphragm TD1



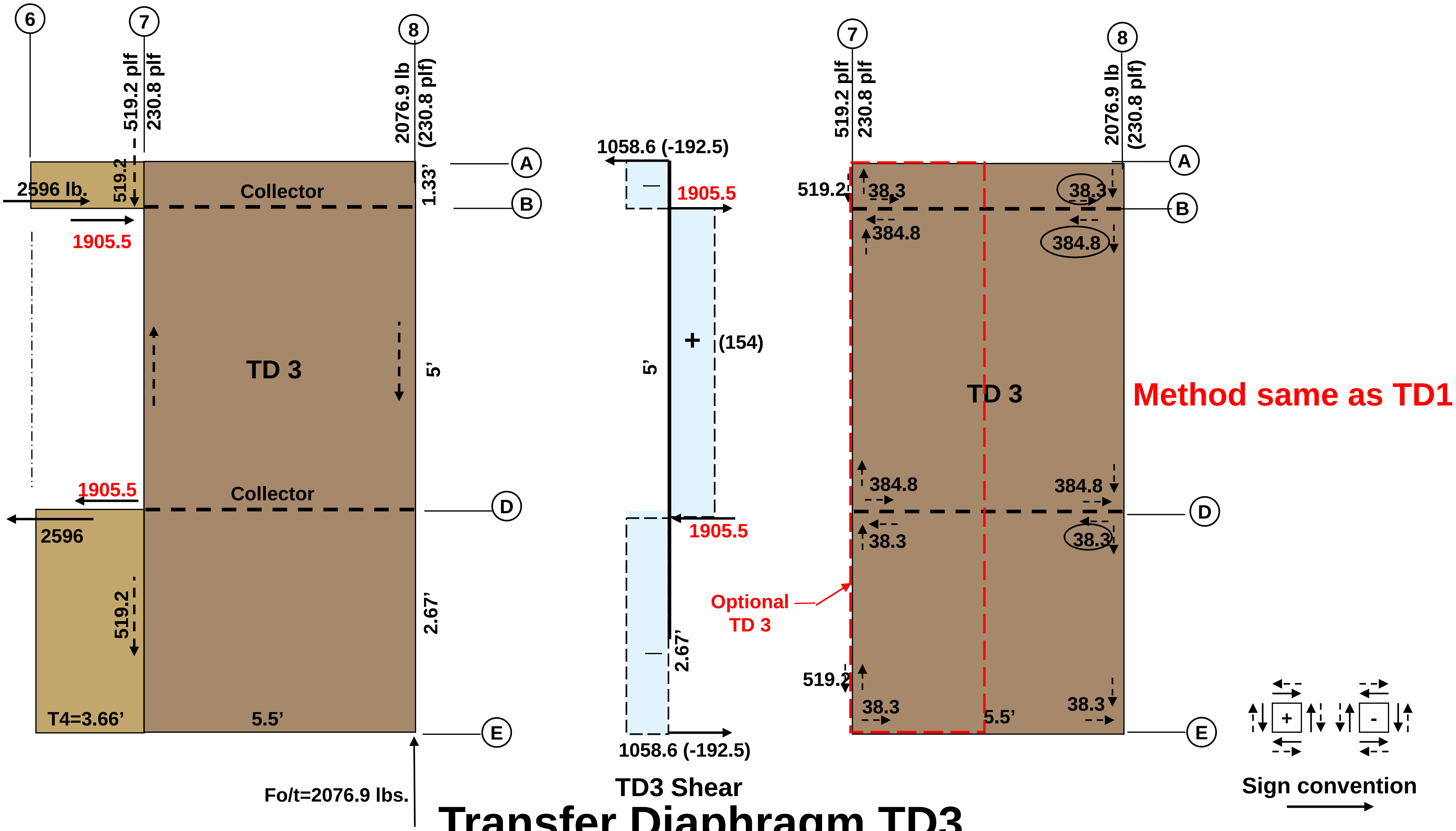
Analyze Transfer Diaphragm 2



Transfer Diaphragm TD2



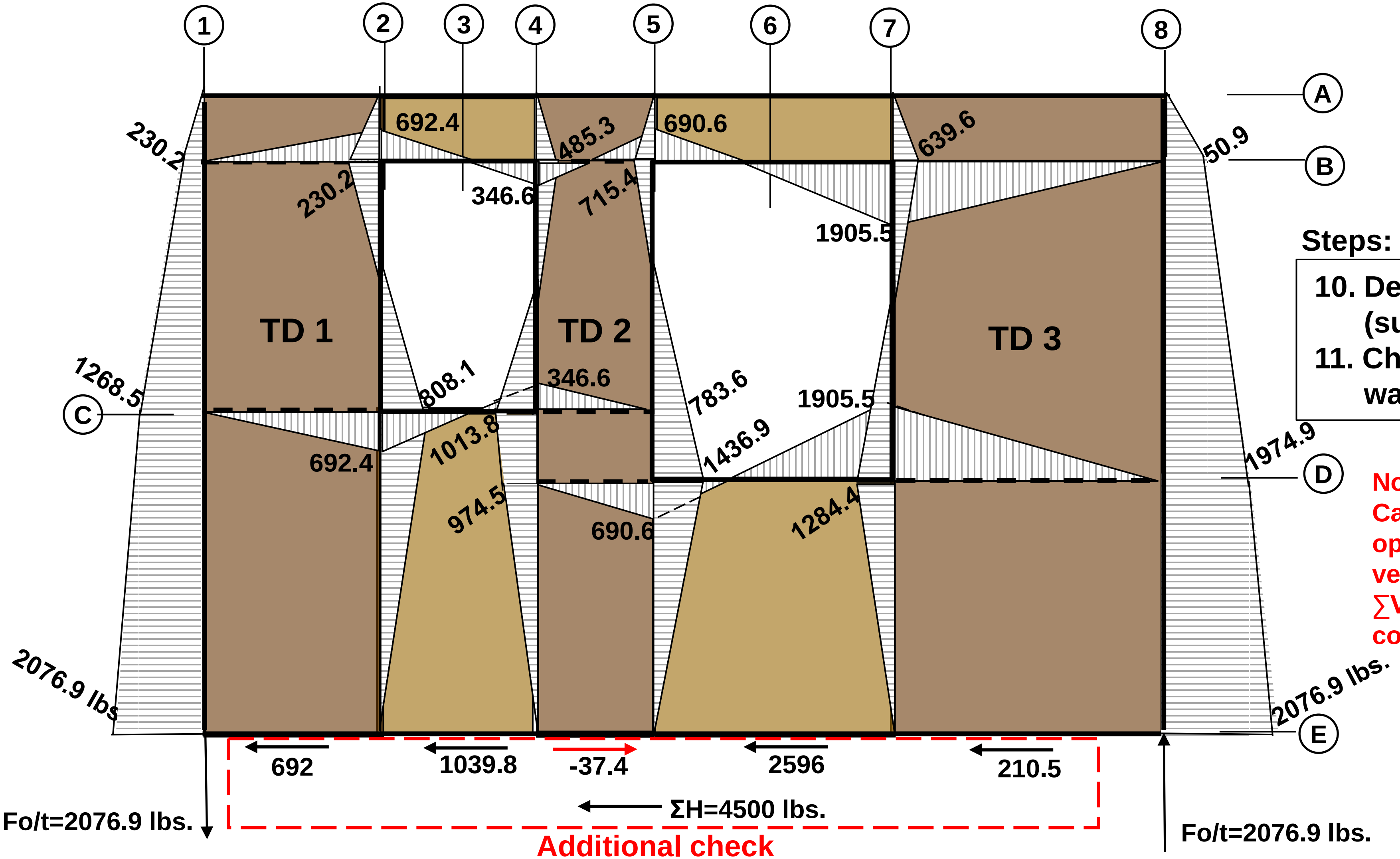
Analyze Transfer Diaphragm 3



Transfer Diaphragm TD3

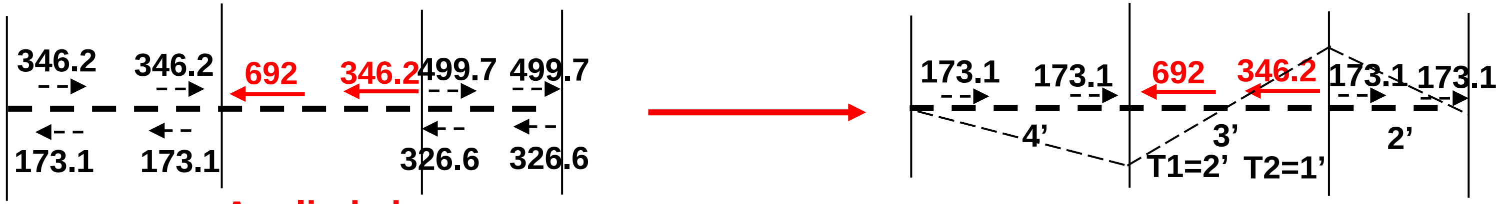
Steps:

10. Develop force diagrams (sum of shears=0)-Optional
11. Check shrs. at bottom of wall sum of shears=0)



Note:
Calculating force diagrams is optional but should be done to verify horizontal and vertical ∑V=0. Verifies analysis is correct.

Example: Grid line C from 1 to 5

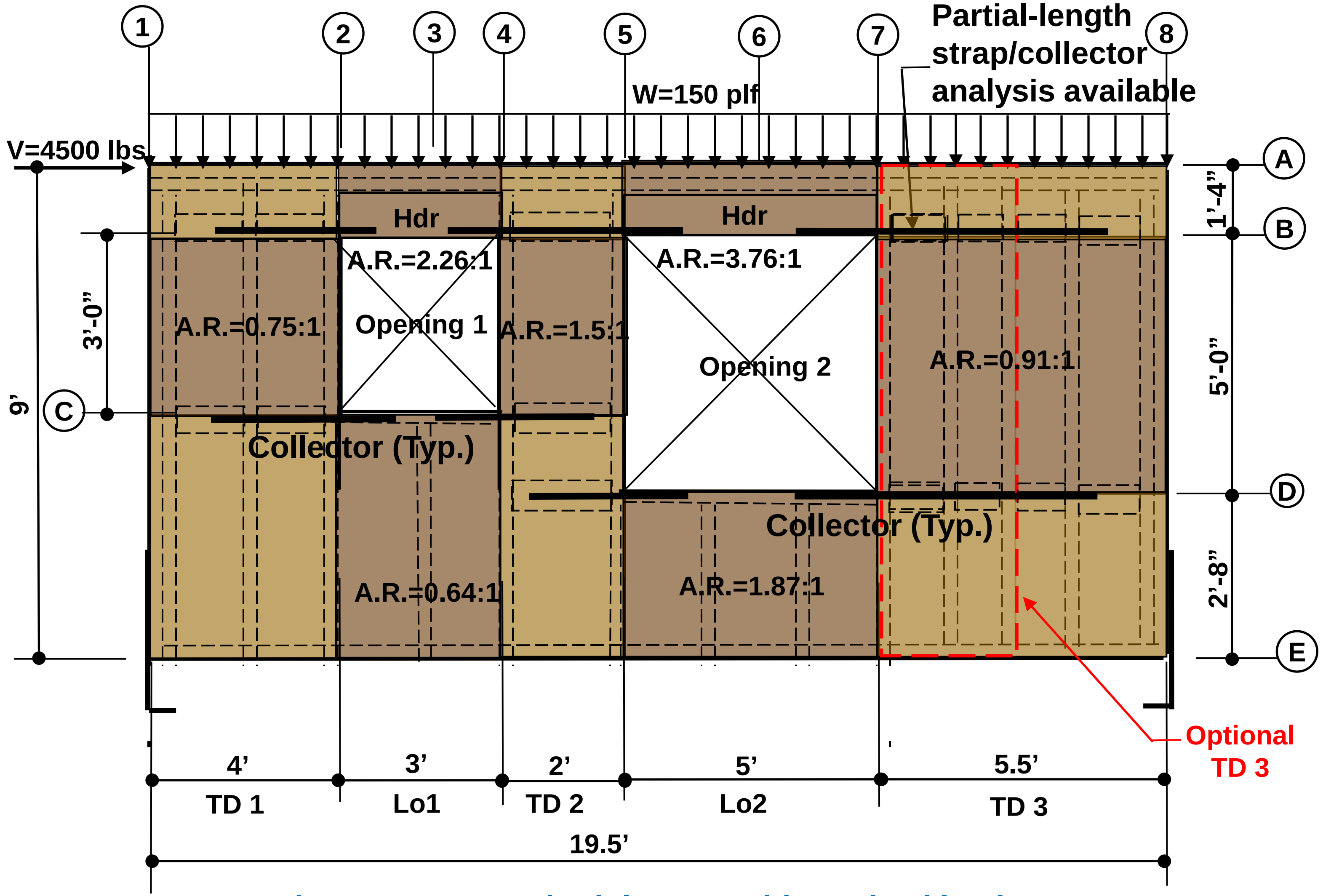


Applied shears

Net shears/forces

Calculate Forces Diagrams

Example 2-Force Transfer Around Opening (FTAO)
Transfer Diaphragm Method -With Dead loads



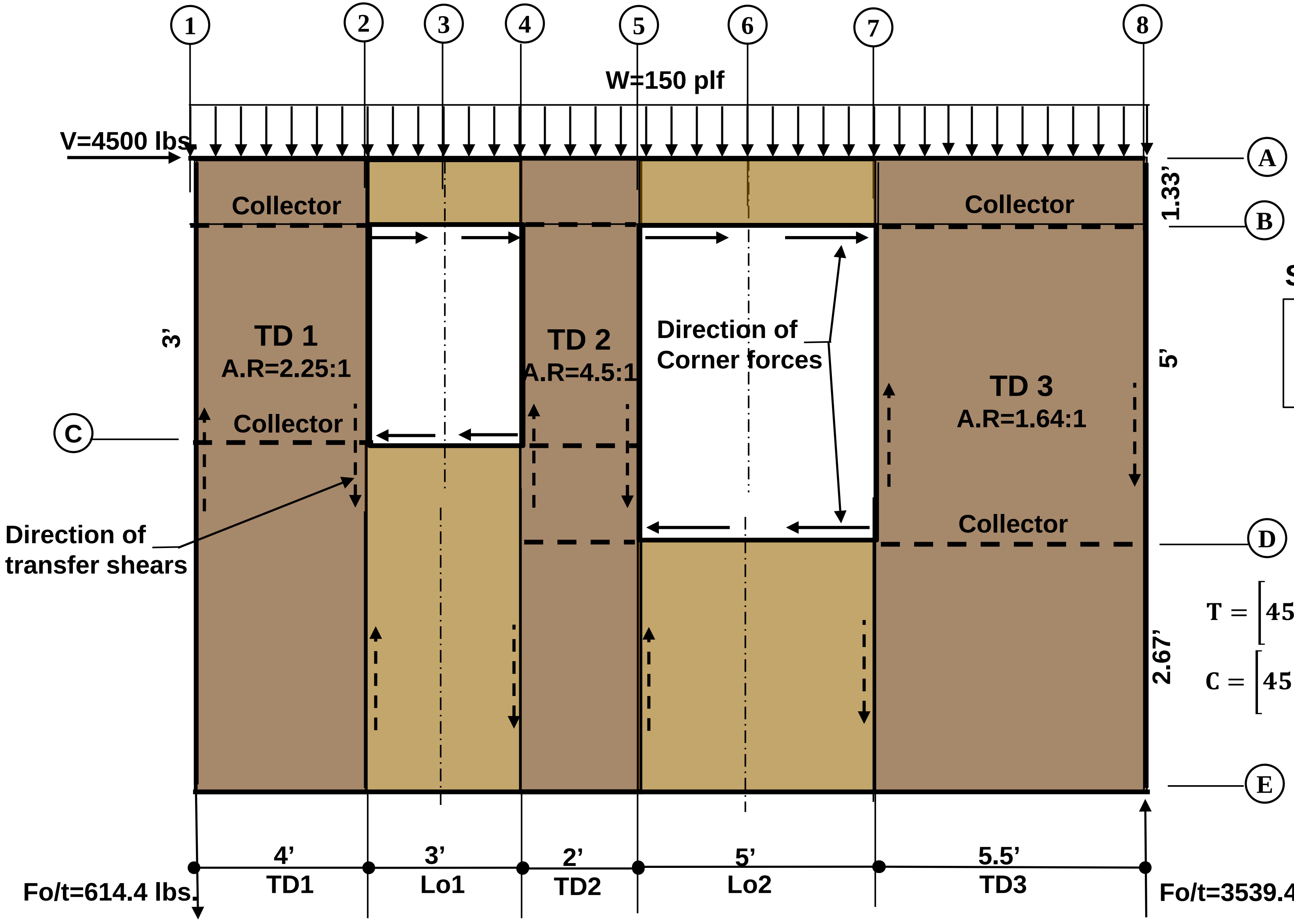
Using same TD methodology as without dead loads

Note: All loads used in these examples have been factored for the load combination used.

- Application of dead loads assumes that the wall or wall segment has a length that is sufficient to allow rigid body action.
- Assumes wall or wall section can be judged to be rigid.

Steps:

1. Determine A.R. of piers, headers, and sill sections



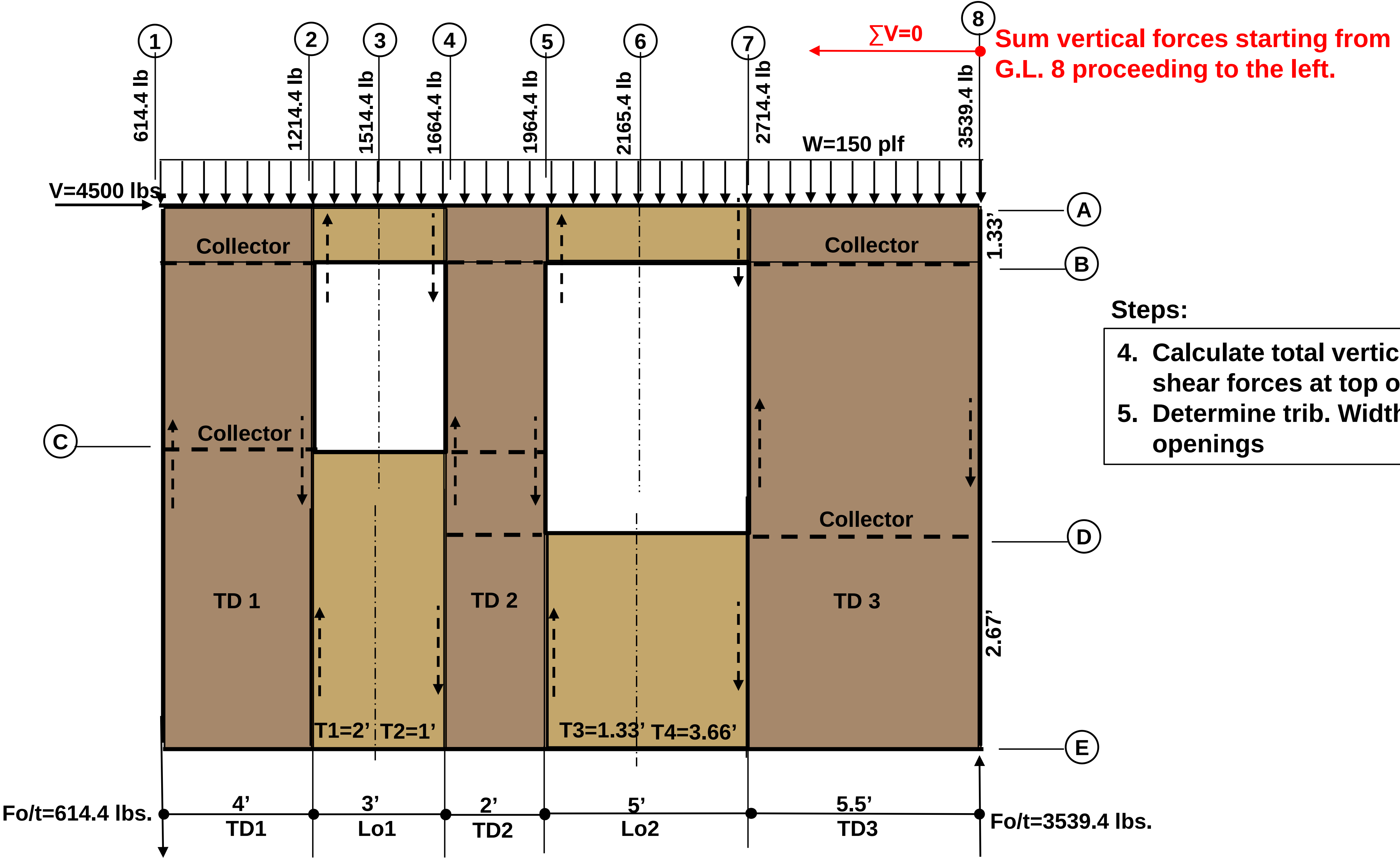
Steps:

2. Calculate O/T forces
3. Determine A.R. of TD

$$\mathbf{T} = \left[4500(9) - \frac{150(19.5)^2}{2}\right]\frac{1}{19.5} = 614.4\ \text{lbs.}$$

$$\mathbf{C} = \left[4500(9) + \frac{150(19.5)^2}{2}\right]\frac{1}{19.5} = 3539.4\ \text{lbs.}$$

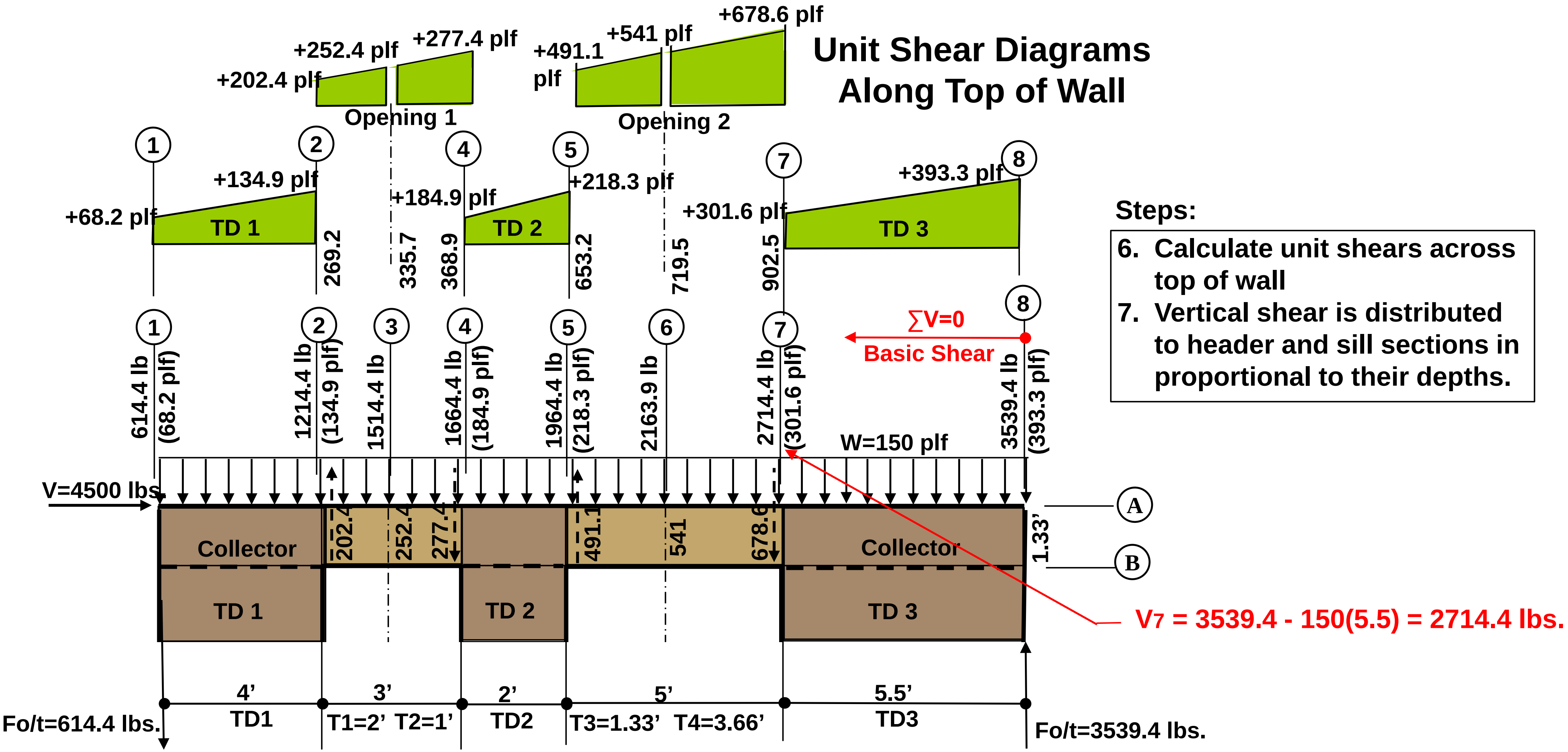
Calculate O/T Forces



Steps:

4. Calculate total vertical shear forces at top of wall.
5. Determine trib. Widths at openings

Calculate Vertical Shear Forces

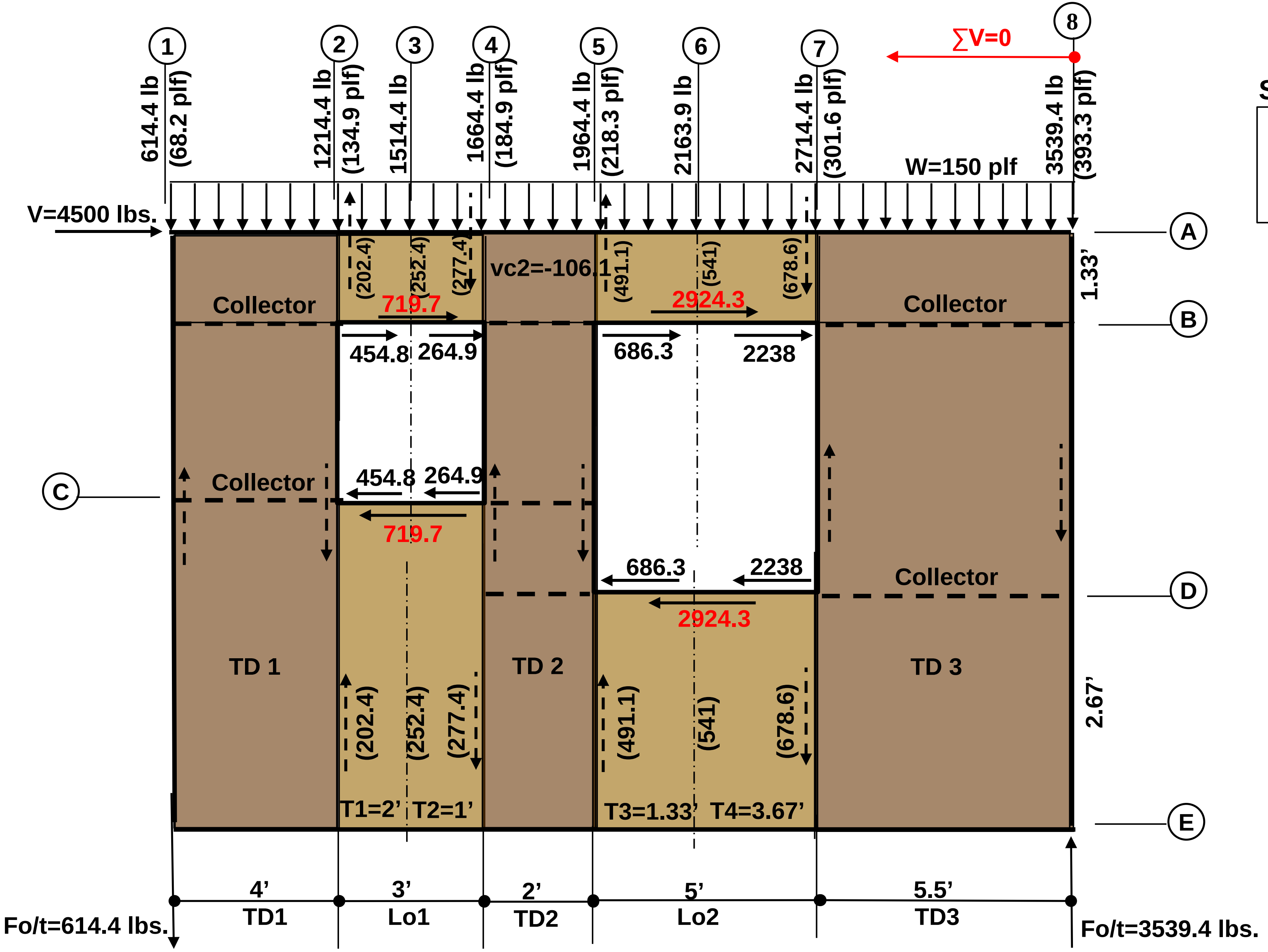


Steps:

6. Calculate unit shears across top of wall
7. Vertical shear is distributed to header and sill sections in proportional to their depths.

Calculate Vertical <u>Unit</u> Shears

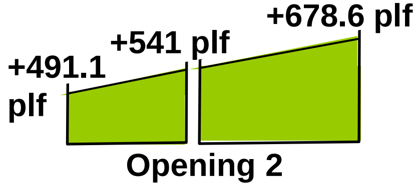
Shears vary linearly across wall



Steps:

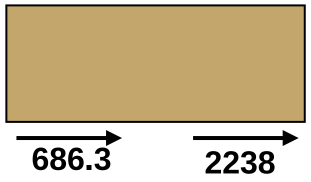
8. Calculate forces to hdrs.
9. Calculate trib. forces at hdrs. and sills

Calculate forces to header Lo2



$F_{hdr} = Lo2(v5+v7)/2$
$= 5(491.1+678.6)/2=2924.3$ lbs.

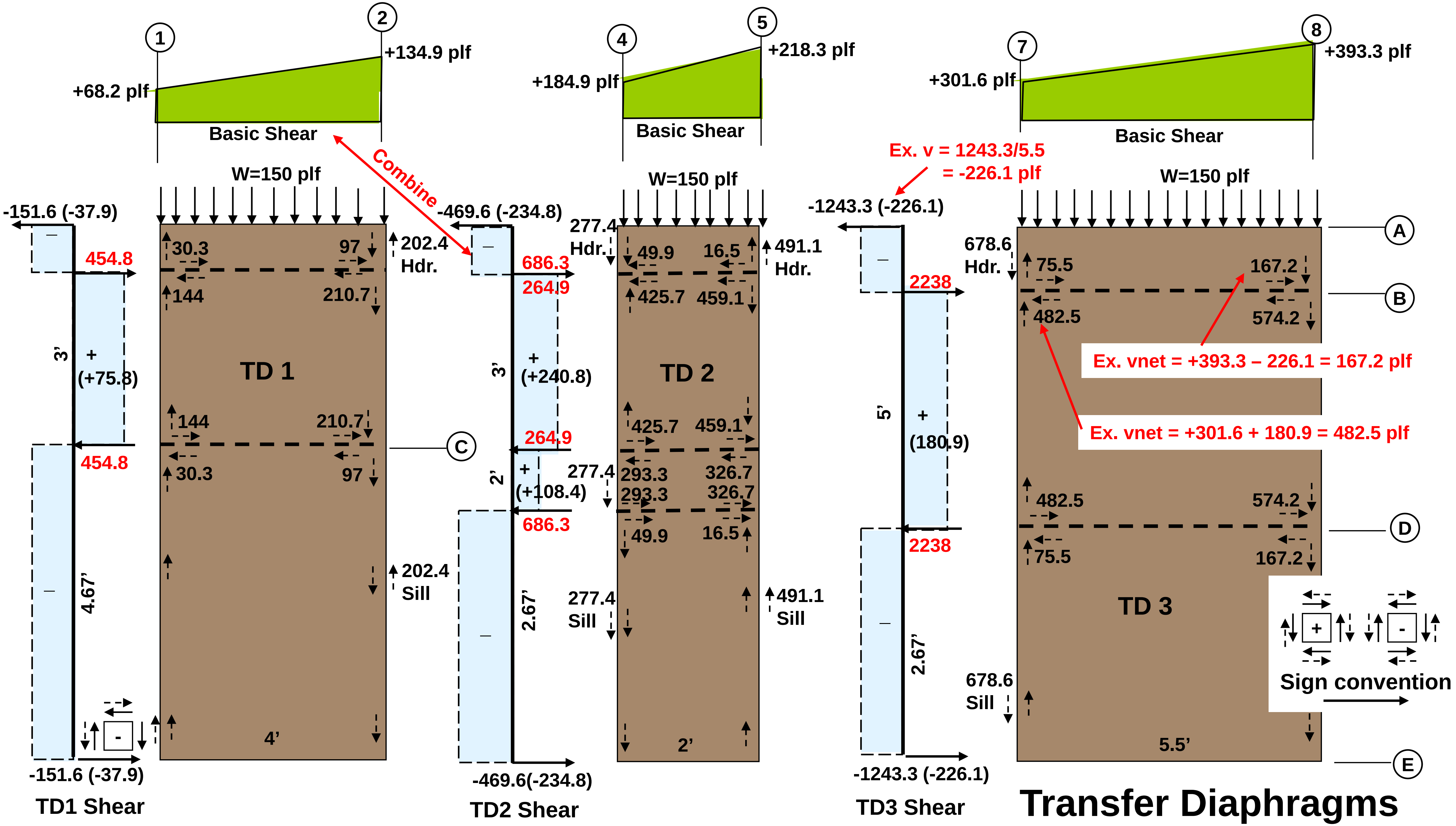
Calculate trib. forces to header



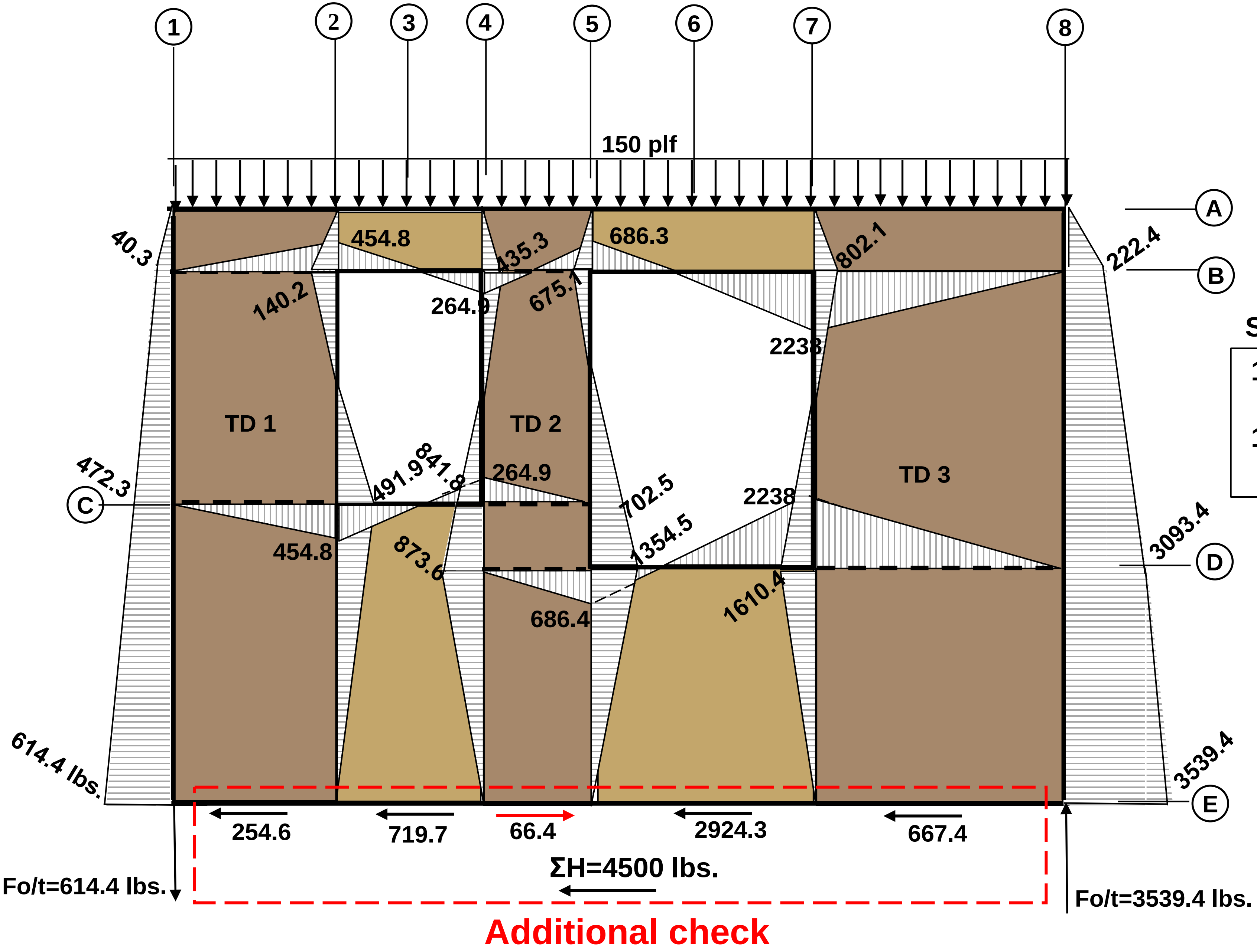
$F_{o2\ left} = T3(v5+v6)/2$
$= 1.33(491.1+541)/2=686.3$ lbs.

$F_{o2\ right} = T4(v6+v7)/2$
$=3.67(541+678.6)/2=2238$ lbs.

Tributary Widths, corner Forces and Shear Forces



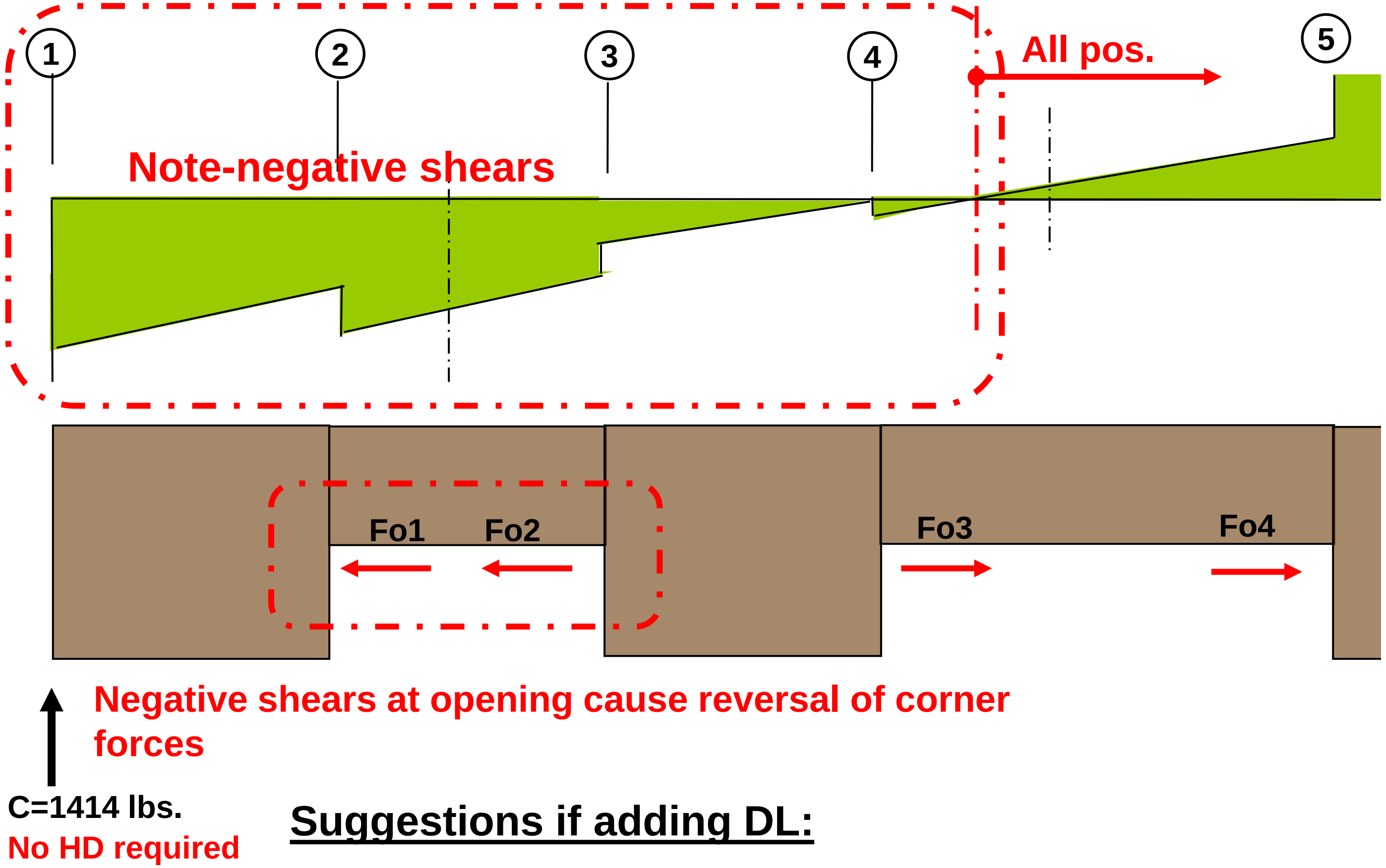
Transfer Diaphragms



Steps:

10. Develop force diagrams (sum of shears=0)
11. Check shears at bottom of wall sum of shears=0)

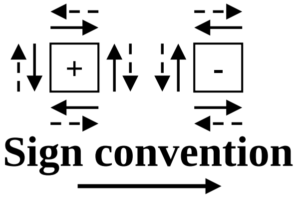
Force Diagrams



Suggestions if adding DL:

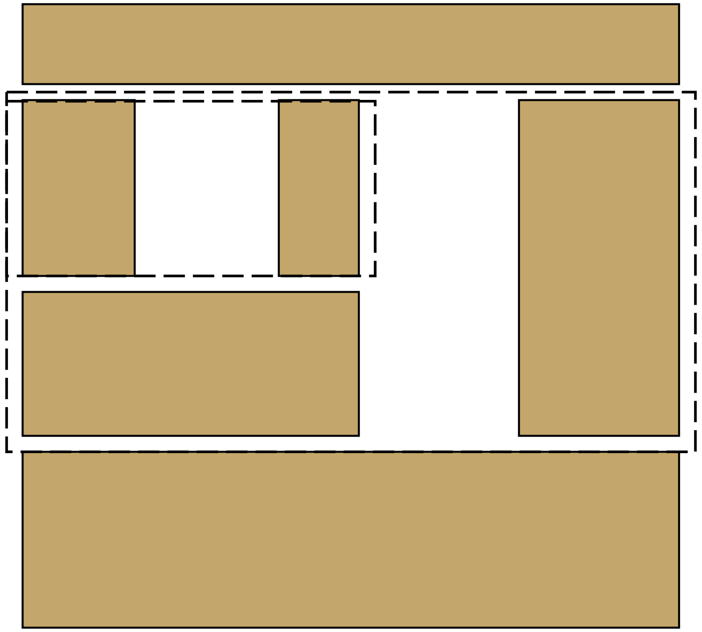
Envelope analysis:

- **Run analysis without DLs to compare maximum corner tension forces.**
- **Compare unit shears in transfer diaphragm for maximum value.**
- **Verify vertical and horizontal collector forces close out to zero.**

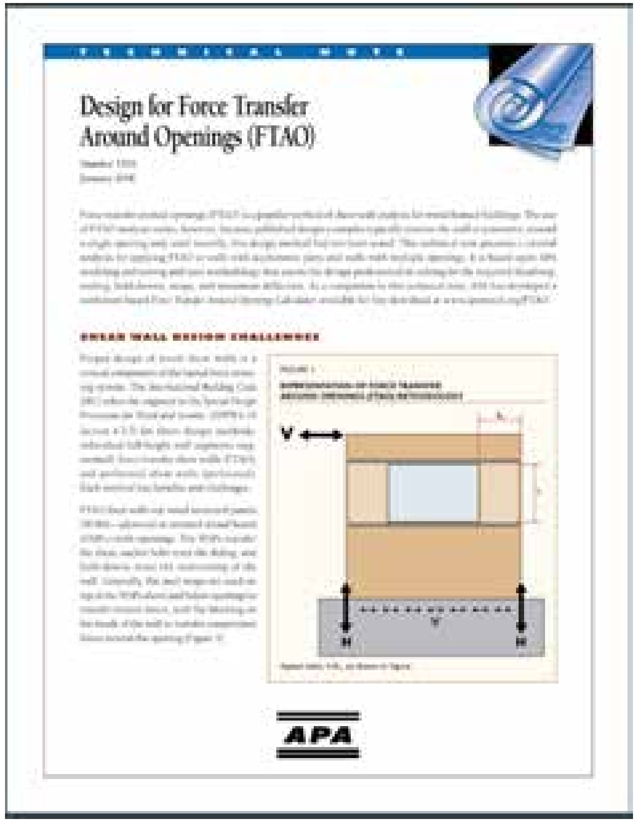


What Happens if No Tension Force?
How does shear flow through wall?

Methods of Calculating Deflection



Or


Design for Force Transfer
Around Openings (FTAO)

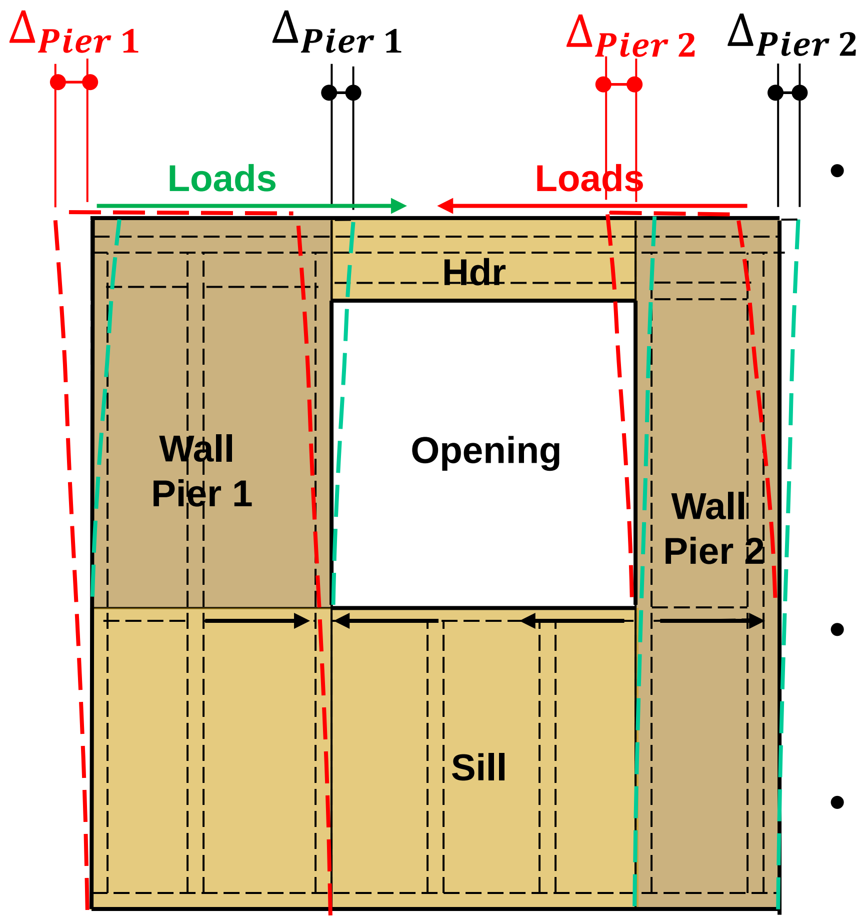
SHEAR WALL DESIGN CHALLENGES

APA

Center strip Method
(Similar to masonry wall)

- **Suggest using Nominal Shear Stiffness for determining wall stiffness.**
- **Fixity of pier sections???**

APA Method



- The deflection of the wall is the average of the deflection of the piers as shown (acting both directions combined) using the 4-term eq.

Single opening

$$\Delta_{Aver.} = \frac{(\overrightarrow{\Delta_{pier\ 1}+\Delta_{pier\ 2}})+(\overleftarrow{\Delta_{pier\ 1}+\Delta_{pier\ 2}})}{4}$$

- The remainder of the terms are identical to the traditional equation.

- Deflections for a wall with multiple openings is similar.

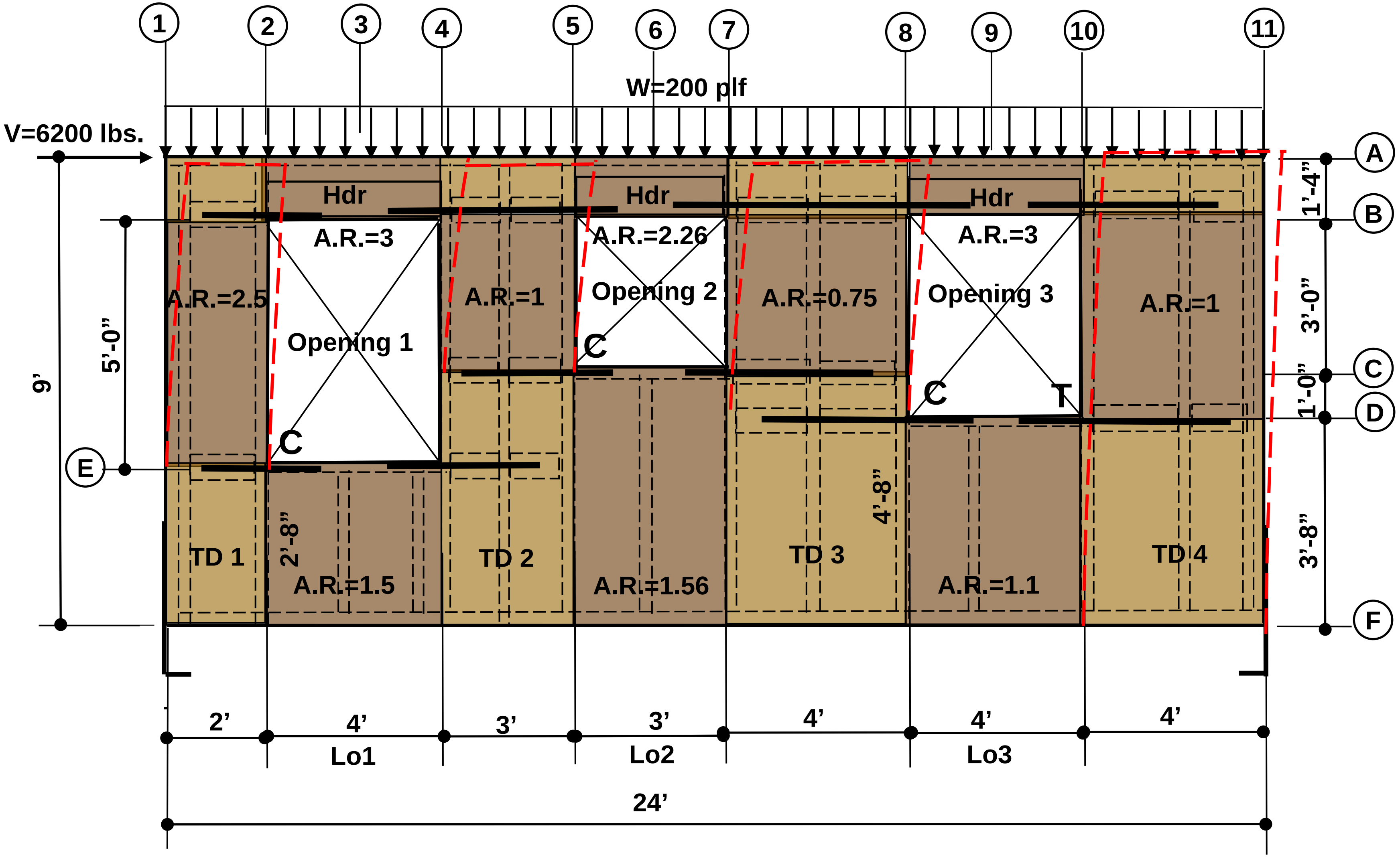
$$\Delta_{Aver.} = \frac{(\overrightarrow{\Delta_{pier\ 1}+\Delta_{pier\ 2}+\Delta_{pier\ 3}})+(\overleftarrow{\Delta_{pier\ 1}+\Delta_{pier\ 2}+\Delta_{pier\ 3}})}{6} \ldots$$

Traditional 4 term deflection equation

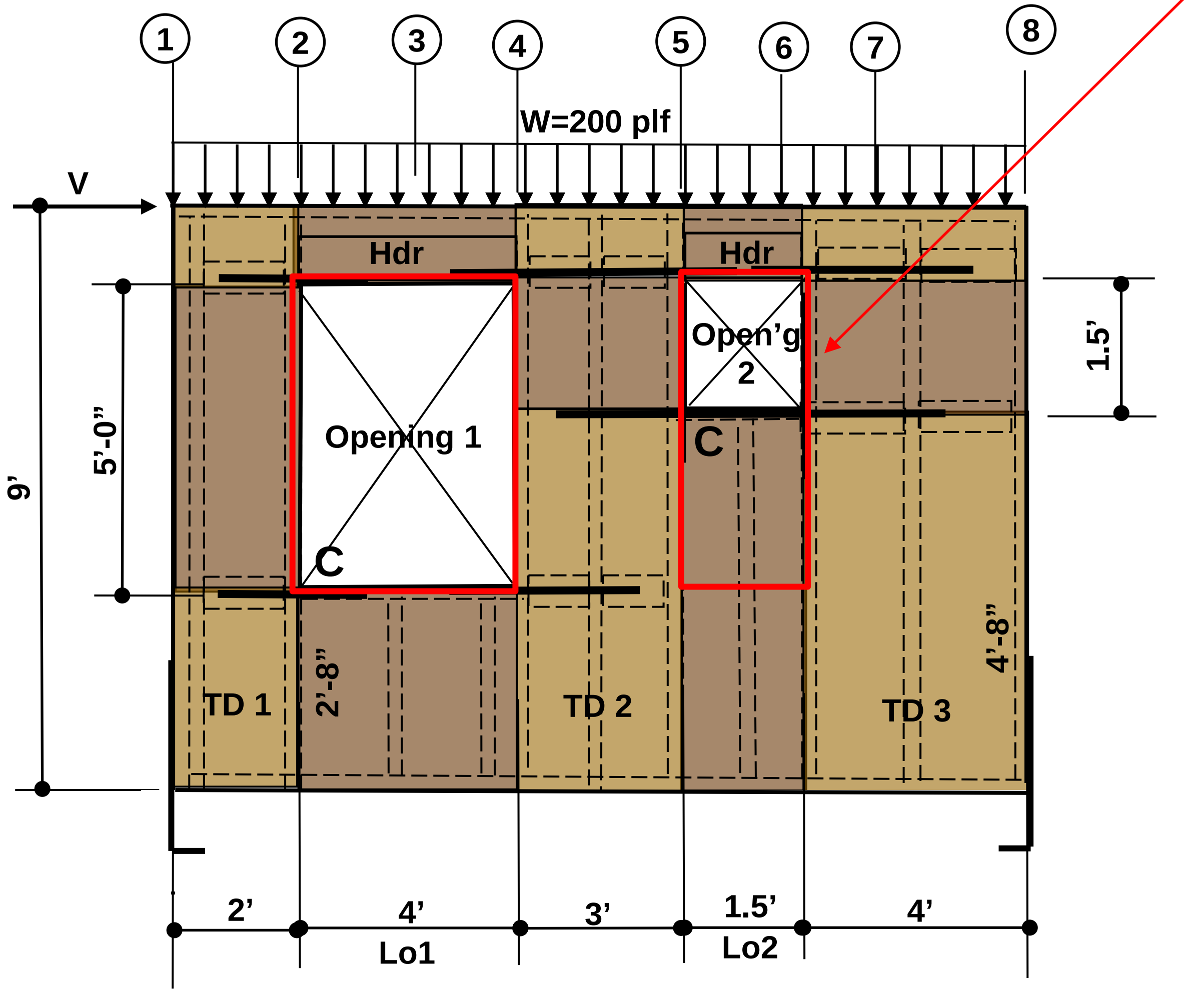
$$\Delta_{SW} = \frac{8vh^3}{EAb} + \frac{vh}{G_v t_v} + 0.75he_n + \frac{h\Delta_a}{b}$$

APA Deflection Method

Reference APA T555



APA Deflection Method?



Is opening small enough to ignore???

FPInnovations(Diaphragms):

Hgt. opening< 0.15 Wdiaph.

Width opening<0.15 Ldiaph.

End dist.> 3x width of opening

FPI Concepts applied to SW's:

Hgt. opening< 0.15 Hwall.

Width opening<0.15 Lwall.

End/edge dist.> 3x width of opening

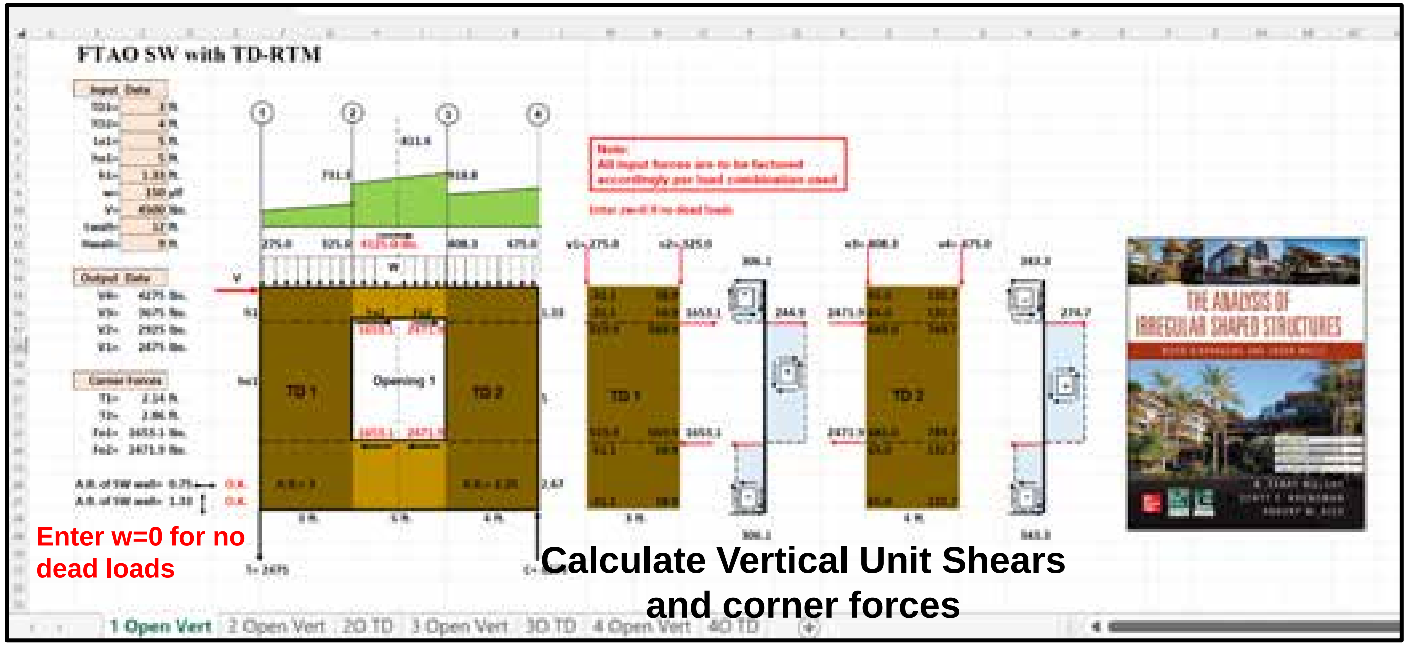
Conservative for shear values but not stiffness

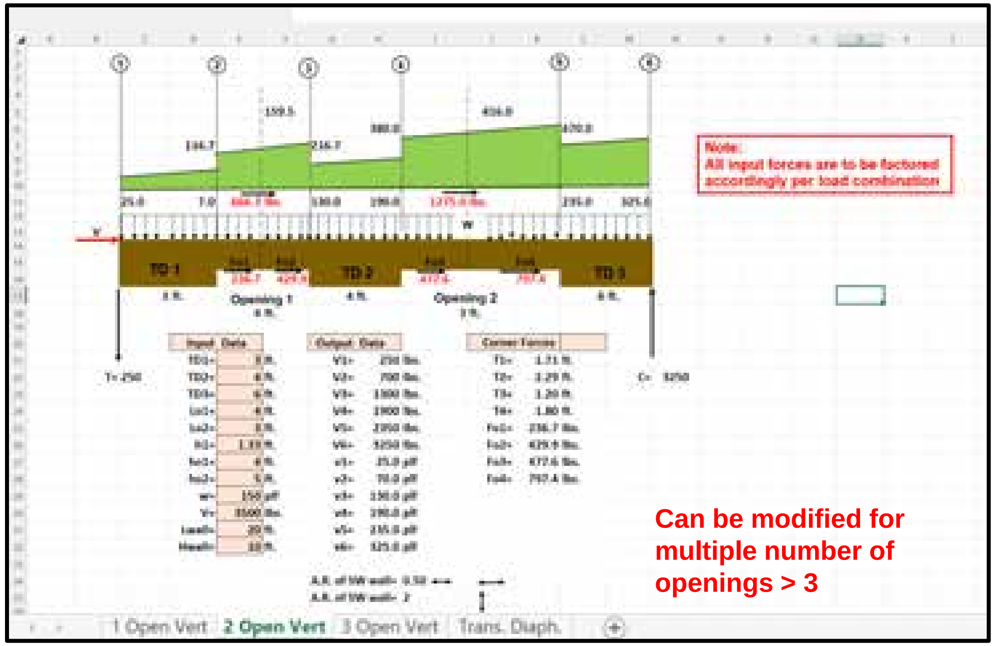
- The greater the deflection, the smaller the stiffness.
- The less stiffness, the less force it attracts under a rigid diaphragm analysis.
- Rigid diaphragm analysis: The wall can be actually stiffer than calculated which could attract more force than it was designed for.

Wall Stiffness?

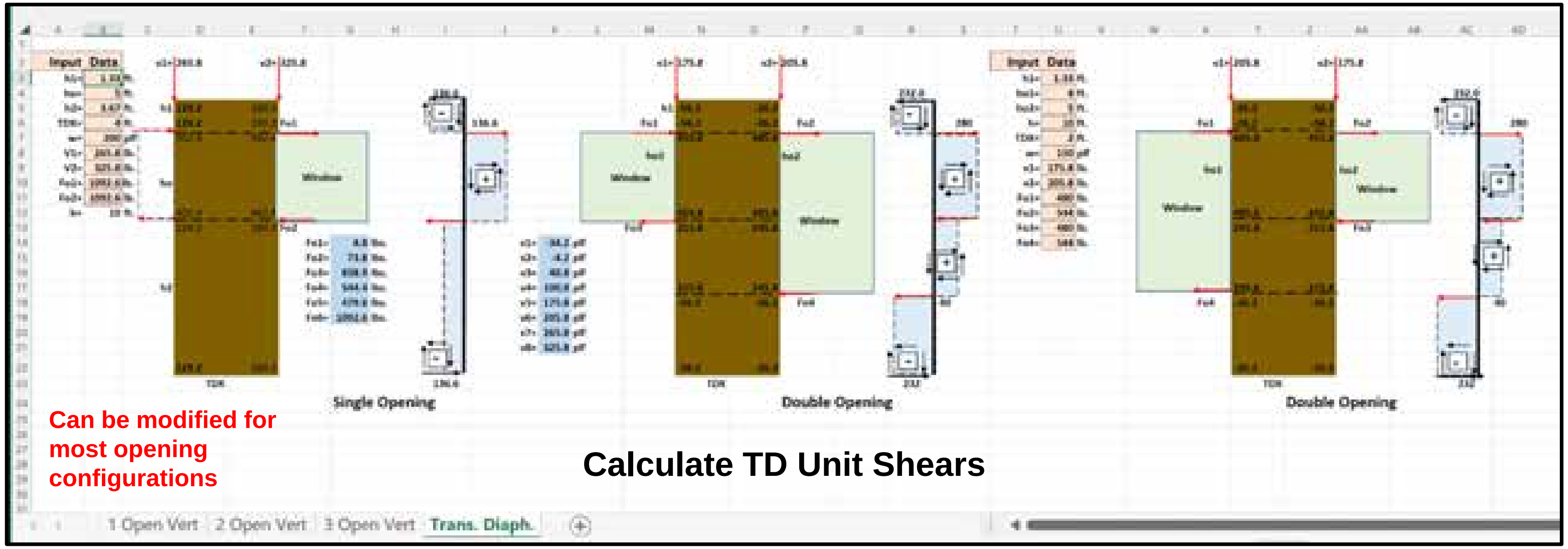
Requires engineering judgement

In-house Time Saver Spreadsheets-Used for development and verification of method





3 and 4 openings not shown



QUESTIONS?

This concludes The American Institute of Architects Continuing Education Systems Course

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