Cantilever Wood Diaphragm Webinar Series

A Design Example of a Wood Cantilever Diaphragm

Part 1-Code Requirements and Relative Stiffness issues

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Course Description

Part 1 of the series will address code requirements and relative stiffness issues associated with cantilever diaphragms in wood structures. Traditionally, wood-frame diaphragms are designed as flexible, meaning that shear forces are transferred to vertical-resisting systems based on tributary widths. However, cantilever diaphragms are required to be analyzed as semi-rigid or rigid, where distribution of shear forces is a function of relative stiffness of the supporting walls rather than tributary widths. This webinar will introduce unique conditions often found in structures that utilize cantilever diaphragms, including increased building heights, multi-story shear wall effects, and torsional irregularities. Current and future code provisions relative to cantilever wood diaphragms will also be discussed.

Learning Objectives

1. **Discuss evolutions in mid-rise building typology that have led to the need for open-front diaphragm analysis.**
2. **Review diaphragm flexibility provisions in ASCE 7 and the 2015 Special Design Provisions for Wind & Seismic (SDPWS).**
3. **Explore one option for open-front diaphragm analysis under seismic and wind loading in a wood-frame structure.**
4. **Highlight how to calculate story drift, diaphragm deflection and torsional irregularities, and discover their effects on load distribution through a cantilever diaphragm structure.**

Fasten Your Seatbelts

5 out of 5 Calculators

WoodWorks Example and Method of Analysis:

- **Currently, there are few, if any, examples or guidance available.**
- **No set path for design.**
- **Codes and standards only partially address open-front design issues.**
- **The solutions paper and this webinar were developed independently from the AWC task group for open-front diaphragms. The method of analysis used in this example is based on our engineering judgement, experience, and interpretation of codes and standards as to how they might relate to open-front structures.**

Cantilever Wood Diaphragm Webinar Series-Content

Webinar Part 1- Code Requirements and Relative Stiffness issues:

- Introduction
- Questions needing resolution
- Horizontal distribution of shear and stiffness issues
- 2015 SDPWS open-front requirements
- Review preliminary design assumptions

Webinar Part 2- Shear Wall Design in Cantilever Diaphragm Structures:

- Introduction to open-front example
- Calculation of seismic forces and distribution
- Preliminary shear wall design
- Nominal shear wall stiffness
- Verification of shear wall design

Webinar Part 3- Cantilever Diaphragm Design, Flexibility and Drift Checks :

- Diaphragm design
- Maximum diaphragm chord force
- Diaphragm flexibility
- Story drift

Webinar Part 4- Torsional Irregularity, Other Design Checks, and Final Comments :

- Amplification of accidental torsion
- Redundancy
- Transverse direction design
- Multi-story shear wall effects

Flexibility and Redundancy Design Challenges

16 Powerhouse, Sacramento, CA
D&S Development
LPA Sacramento

Codes and Standards

A variety of challenges often occur on projects due to:

- Fewer opportunities for shear walls at exterior wall lines which cause Open-front diaphragm conditions
- Increased building heights, and
- Potential multi-story shear wall effects.

In mid-rise, multi-family buildings, corridor only shear walls are becoming very popular way to address the lack of capable exterior shear walls.

The goal of this presentation is to provide guidance on how to analyze a double open-front, or corridor only shear wall diaphragm, and help engineers better understand flexibility issues associated with these types of structures.

The analysis techniques provided in this presentation are intended to demonstrate one method of analysis, but not the only means of analysis.

Part 1 Content and Learning Objectives

Code Requirements and Relative Stiffness issues

- **Introduction**
- **Questions needing resolution**

  Discuss the unique Issues involved in the design of a wood cantilever diaphragm.
- **Horizontal distribution of shear and stiffness issues**

  Demonstrate how diaphragm and shear wall flexibility can effect the horizontal distribution of shears within the structure.
- **2015 SDPWS open-front requirements**

  Review current and pending code requirements for cantilever diaphragm designs.
- **Review preliminary design assumptions**

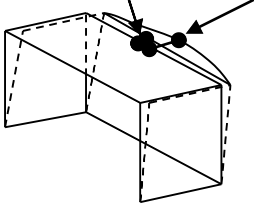
  Discuss the preliminary assumptions that have to be made at the onset of a design.

Questions

1. When does a loss in stiffness in the exterior walls cause an open-front diaphragm condition?
2. What is the deflection equation for open-front/cantilever diaphragms?
3. How is diaphragm flexibility defined for open-front/cantilever diaphragms vs. ASCE 7-16, Figure 12.3-1?
4. What are the available methods of distributing torsional forces into the diaphragm?
5. Do shear walls located along diaphragm chord lines affect the diaphragm chord forces?
6. Will the in-plane lateral forces of the exterior walls located at the ends of the cantilever increase chord forces, or is it acceptable to include these as part of the PSF lateral load?
7. How are torsional irregularities determined and addressed for open-front/cantilever diaphragms?

Horizontal Distribution of shear and Stiffness Issues

Distribution of shear to vertical resisting elements shall be based on an analysis where the diaphragm is modeled as:



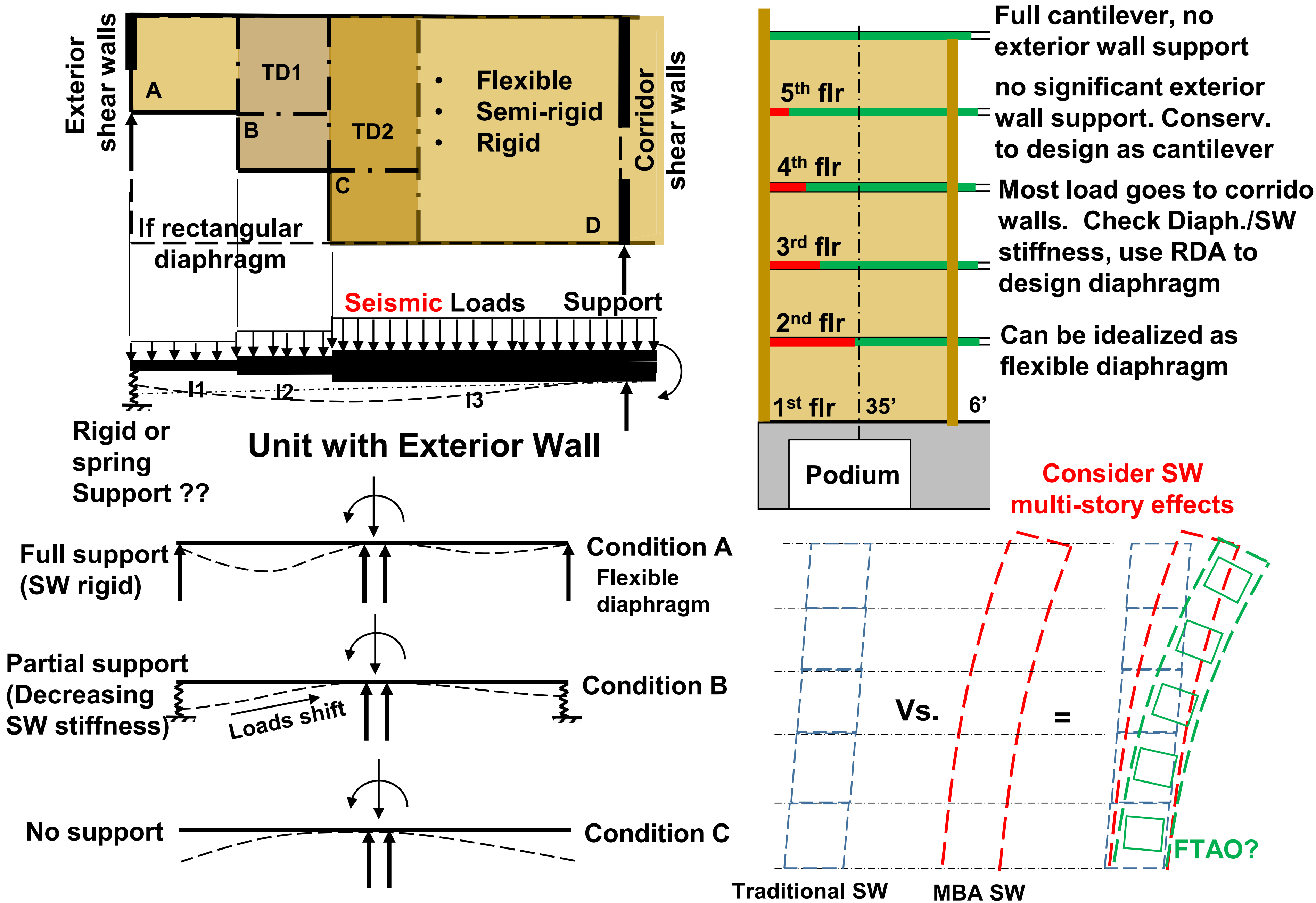
Maximum diaphragm deflection (MDD) >2x average story drift of vertical elements, using the ELF Procedure of Section 12.8?

Calculated as Flexible

- **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.**
  - More conservatively distributes lateral forces to corridor, exterior and party walls
  - Allows easier determination of building drift
  - Can over-estimate torsional drift
  - Can also inaccurately estimate diaphragm shear forces
- **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.
  - In lieu of a semi-rigid diaphragm analysis, it shall be permitted to use an enveloped analysis.

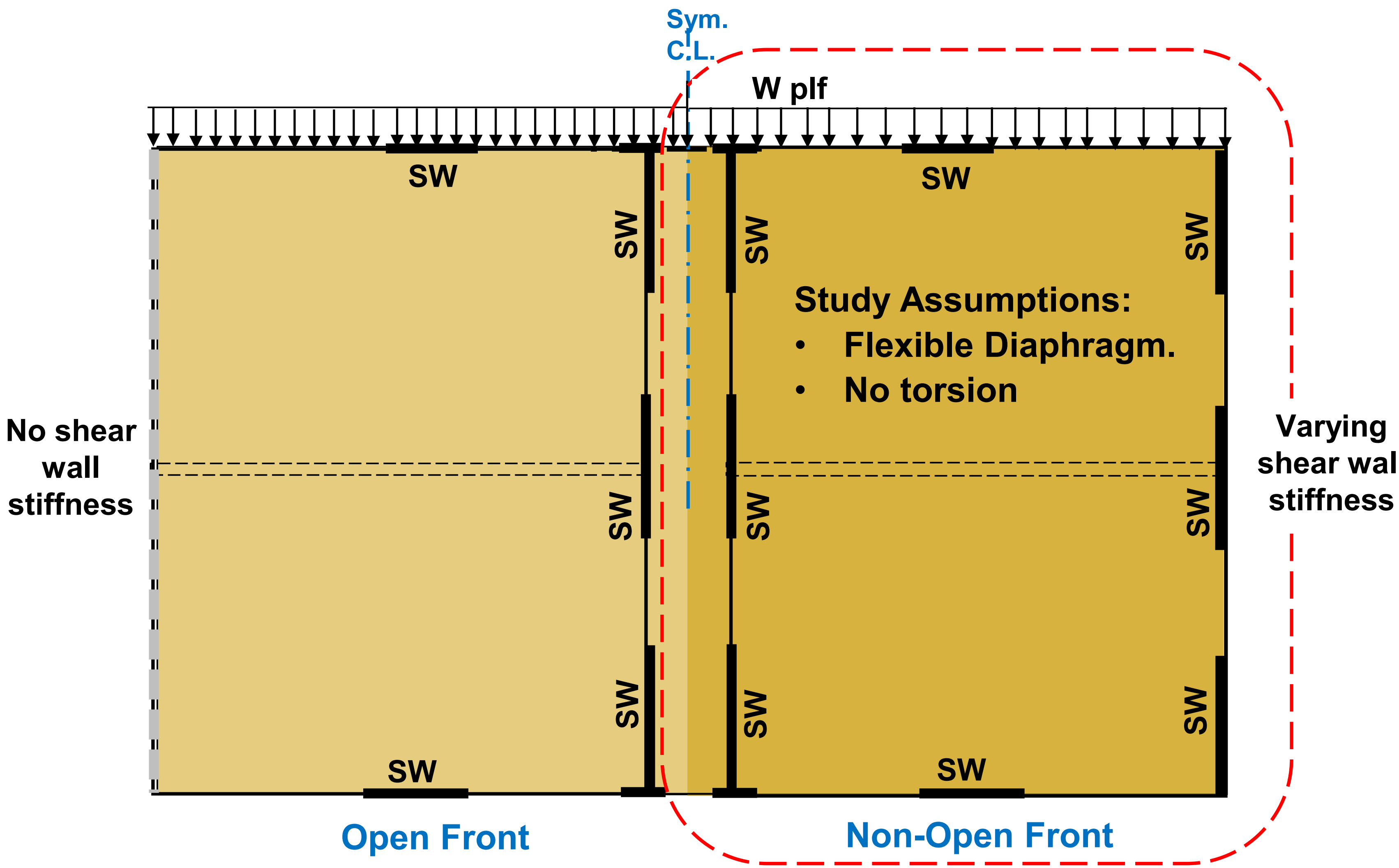
Note:
Offsets in diaphragms can also affect the distribution of shear in the diaphragm due to changes in the diaphragm stiffness.

Force Distribution Due to Diaphragm/SW stiffness



Example-Exterior Wall Stiffness- Not in paper

Question 1-When Does a Loss in Stiffness in the Exterior Walls Cause an Open-front Diaphragm Condition? **No magic bullet answer!**



Starting point-Exterior shear walls same number, length, stiffness and construction as corridor walls.

Study to Determine Open-front condition - 35' Span

Objective is to determine point where loss of shear wall stiffness at exterior wall line causes an open-front condition

- Force distribution to walls based on nominal wall stiffness
- 2D FEA model used to visualize diaphragm displacement curves and force distribution
- Diaphragm 15/32" WSP w/ 10d@6" o.c.
  - Modelled as flexible
  - Continuous chords at corridor walls
- Shear walls with 15/32"WSP
  - Wall height=10'
  - Hold down anchors same for all walls
  - No gravity loads
  - Corridor walls (3)10' w/ 10d@4" o.c.-constant through-out study (basis of design)

10d nails

L=(3)10' walls
- 10d@4"o.c., Ga=30
- 10d@6"o.c., Ga=22

L=(3)8' walls
- 10d@3"o.c., Ga=37
- 10d@4"o.c.
- 10d@6"o.c.

L=(3)6' walls
- 10d@3"o.c.
- 10d@4"o.c.
- 10d@6"o.c.

L=(3)4' walls
- 10d@3"o.c.
- 10d@4"o.c.
- 10d@6"o.c

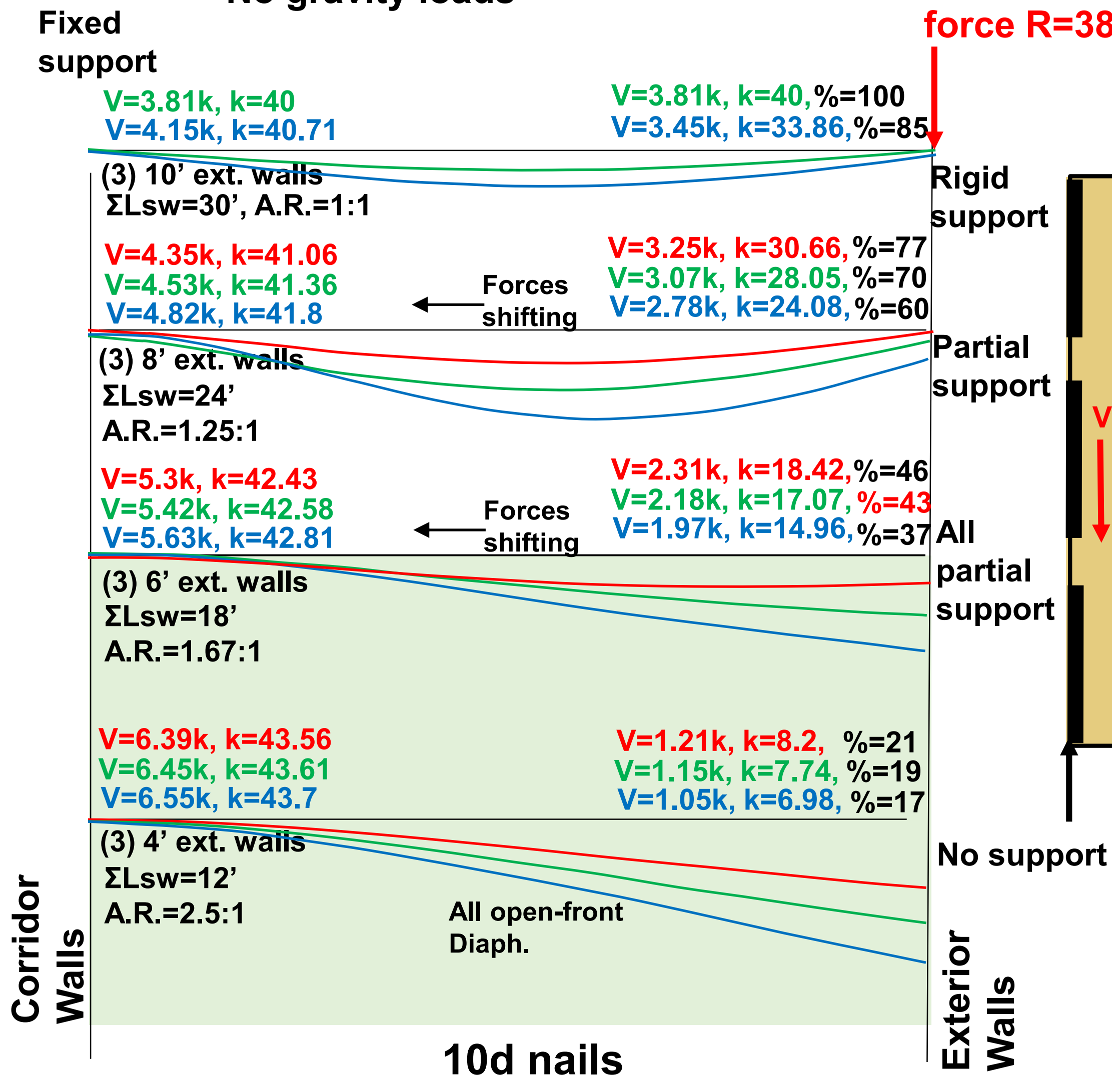
Force Distribution-SW displ.

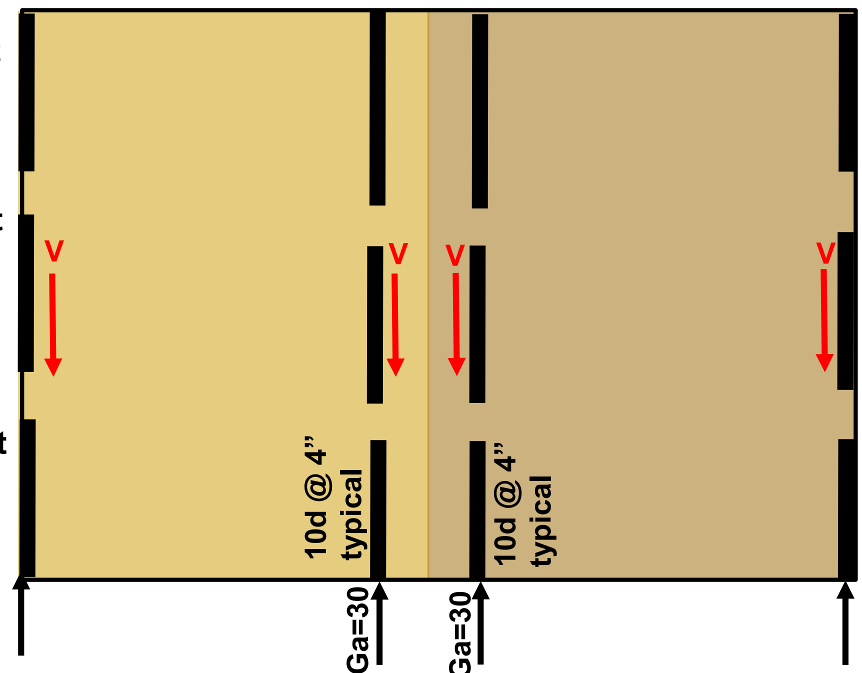
- Diaphragm stiffness flexible
- Shear wall stiffness-variable
- Seismic STR. Forces
- No torsion
- No gravity loads

- V=Shear to wall line
- k=Stiffness of wall line
- %=SW stiffness at exterior wall vs. corridor wall line

3” @ ext. walls
4” @ ext. walls
6” @ ext. walls
Open-front effect

If flexible, trib. Reaction force R=3810 lbs.





Prelim conclusion (This example only):

- If walls near 44% or if k ≤ 20 consider open-font

A matter of Stiffness

Seismic:

ASCE 7-16 Section 12.3.1- Diaphragm flexibility-The structural analysis shall <u>consider</u> the relative stiffnesses of diaphragms and the vertical elements of the seismic force resisting system.

Wind:

ASCE 7-16 Section 27.4.5- Diaphragm flexibility-The structural analysis shall <u>consider</u> the relative stiffness of diaphragms and vertical elements of the MWFRS.

Flexible structures are susceptible to damage from wind or seismic forces

Structures Are Also Susceptible to Wind Damage

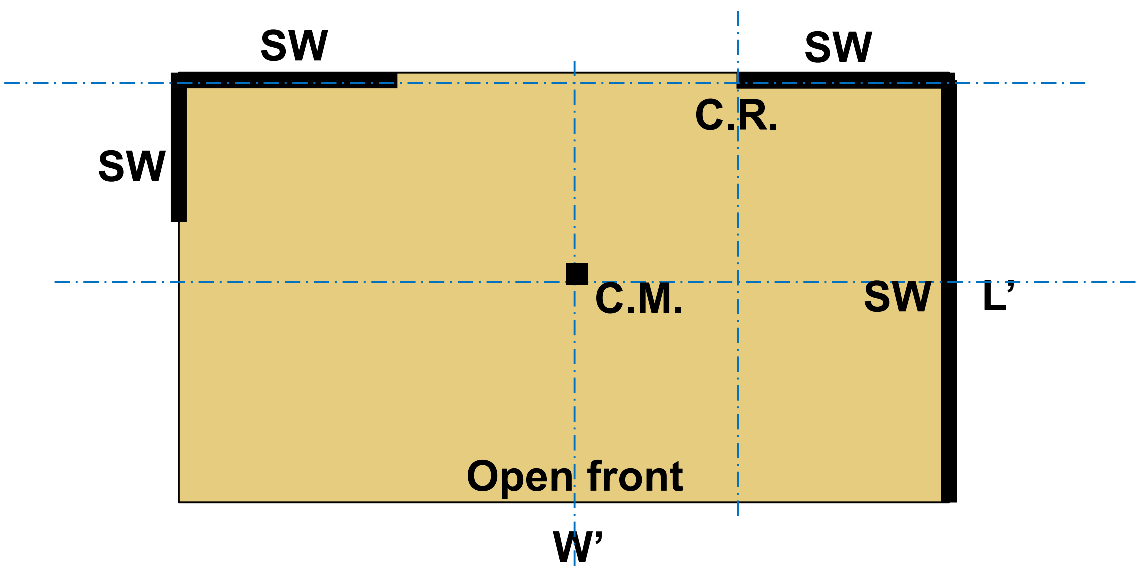
- Too much flexibility?
- Lack of adequate shear walls
- Soft / Weak story issues?
- Insufficient load paths?
- Lack of proper connections?

Possible Soft Story

Possible Soft Story
(Not enough shear walls across front)

2015 SDPWS Open-front Diaphragm Requirements

Open-Front Diaphragms



Relevant 2015 SDPWS Sections

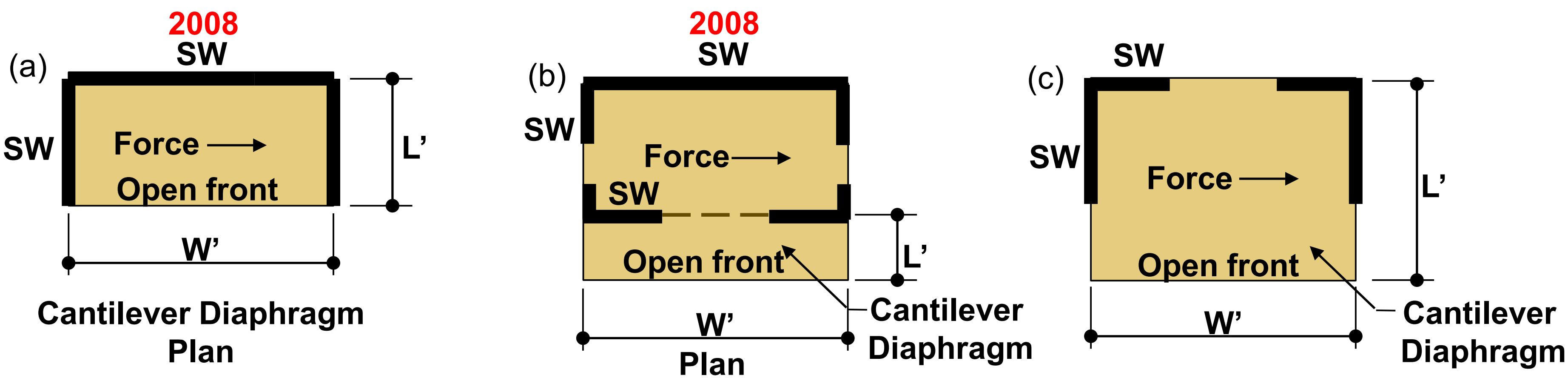


Figure 4A Examples of Open Front Structures

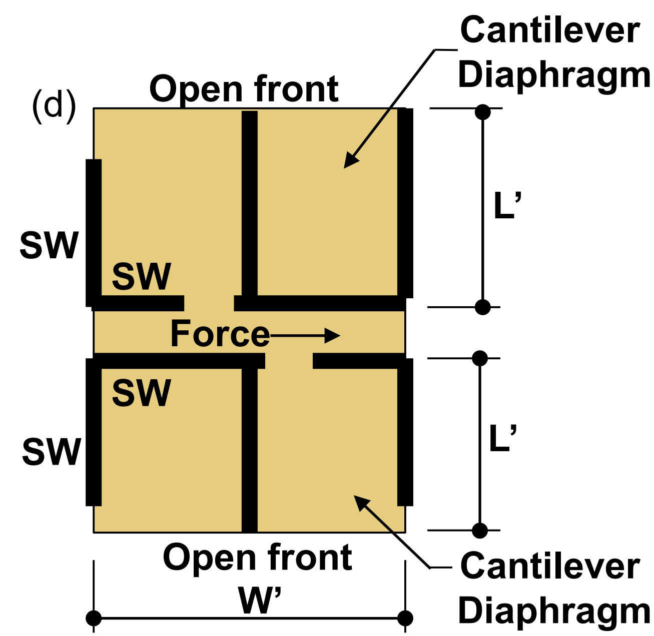
4.2.5.2 Open Front Structures:

New definitions added:

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

Relevant Revised sections:

- 4.2.5- Horizontal Distribution of Shears
- 4.2.5.1-Torsional Irregularity
- 4.2.5.2- Open Front Structures
- Combined open-front and cantilever diaphragms



Similar to MS-MF structures

SDPWS 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 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 over one story in height, and 1:1 for structures one 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.**

5. **The diaphragm length, L', (normal to the open side) does not exceed 35 feet. (2008 SDPWS: L'_{max}=25'. Exception-if drift can be tolerated, L' can be increased by 50%). Could use an Alternative Materials, design and Methods Request (AMMR) to exceed 35'.**

Currently no deflection equations or guidance on determination of diaphragm flexibility.

Open Front Structures Code Checks:

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

1. Verify aspect ratios of diaphragms and shear walls	SDPWS 4.2.5.2 (2), 4.3.4
2. Verify diaphragm length, L'	SDPWS 4.2.5.2(4)
3. Check stiffness of diaphragm and shear walls	ASCE 7 12.3.1, SDPWS 4.2.5.2 (3)
4. Check diaphragm flexibility	ASCE 7 12.3, SDPWS 4.2.5.2 (3)
5. Check drift at edges	ASCE 7 12.8.6, SDPWS 4.2.5.2 (3)
6. Check for torsional irregularity	ASCE 7 12.3.2.1 and 12.3.3, SDPWS 4.2.5.1
• Inherent torsion	ASCE 7 12.8.4.1
• Accidental torsion	ASCE 7 12.8.4.2
• Amplification of accidental torsion	ASCE 7 12.8.4.3
7. Assume or verify redundancy	ASCE 7 12.3.4

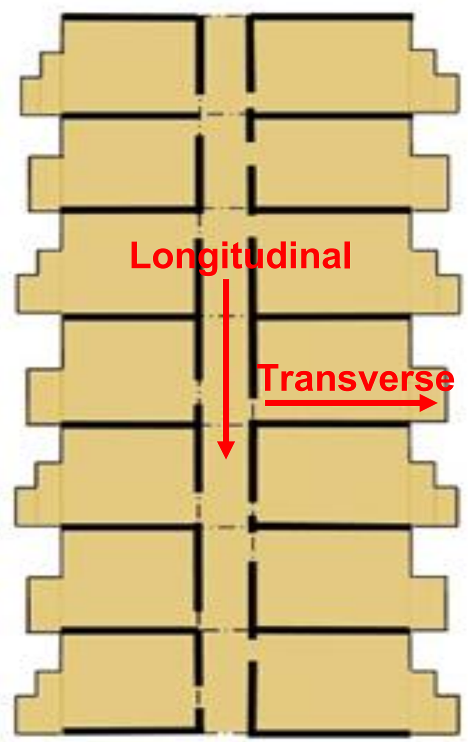
For resistance to Wind loads, recommend complying with all of the following requirements:

- Items 1 thru 4 as noted above.
- Item 5 noted above for wind — ASCE 7 Appendix CC Section CC2.2
- Item 6 -Note: See ASCE 7-16 Appendix CD for buildings exempted from torsional wind load cases.

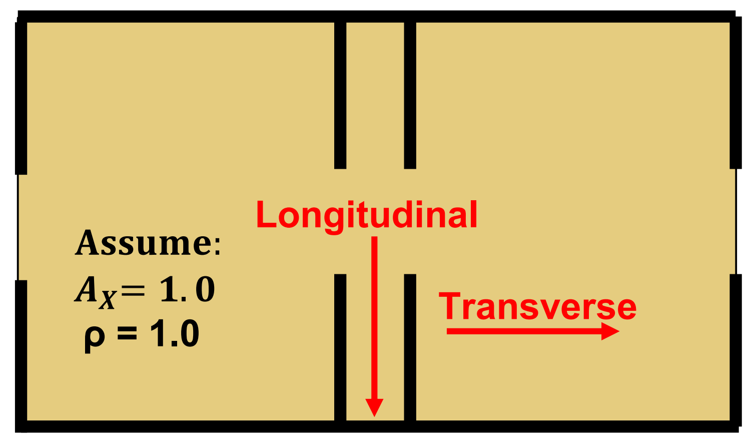
Preliminary Assumptions

Lateral System Plan Layout and Redundancy / Irregularity Issues

1. LFRS Layout - efficient / marginal / scary
2. Diaphragm Flexibility
3. Redundancy
4. Accidental torsion
5. Torsional Irregularities



Assume:
$A_X = 1.0$
ρ = 1.0

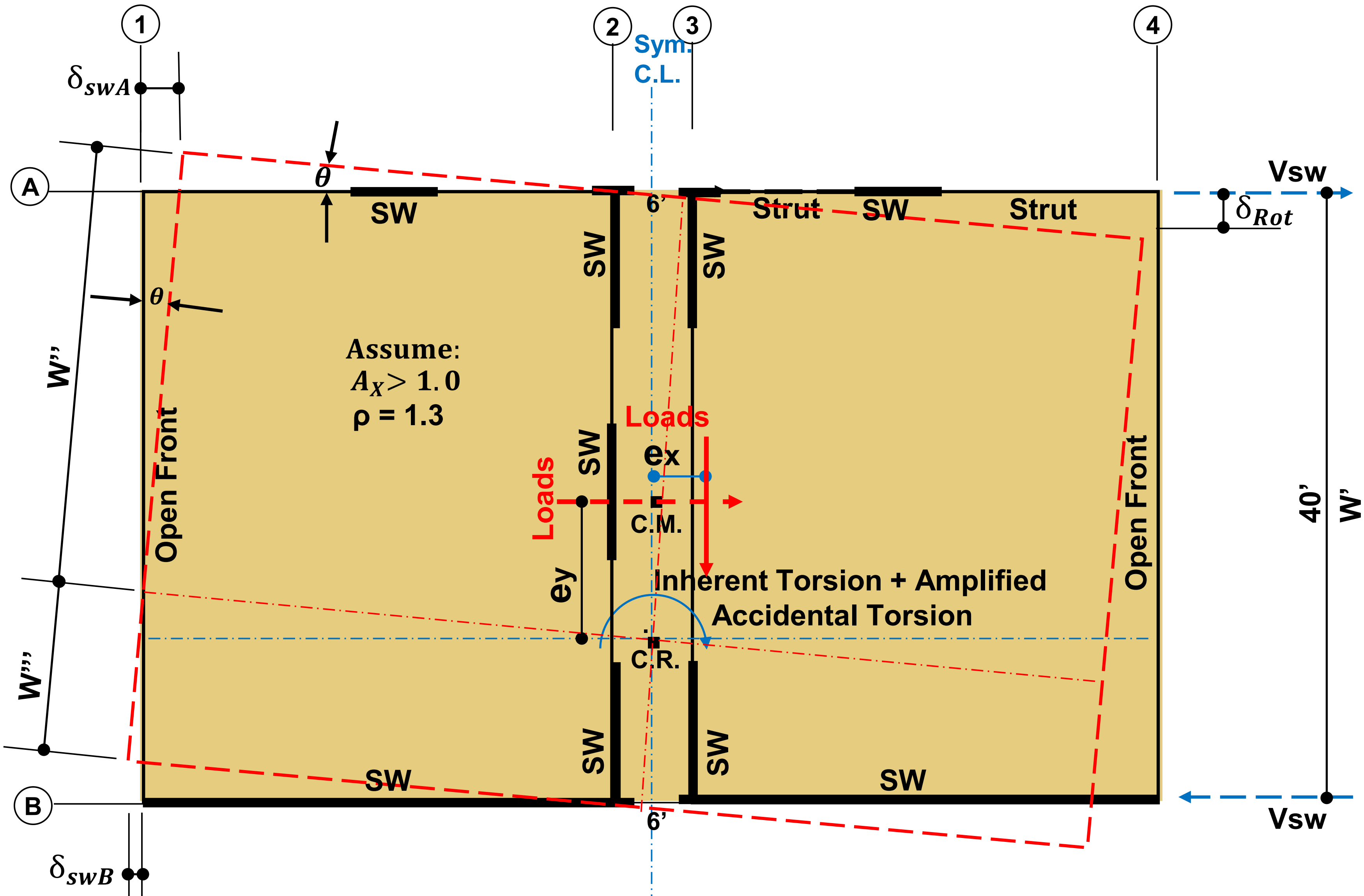


Assume:
$A_X = 1.0$
ρ = 1.0

A_X= Amplification of accidental torsion if torsional irregularity exists
ρ = Redundancy

Regular Plans

Questionable Plans-Unsymmetrical Plan Layouts



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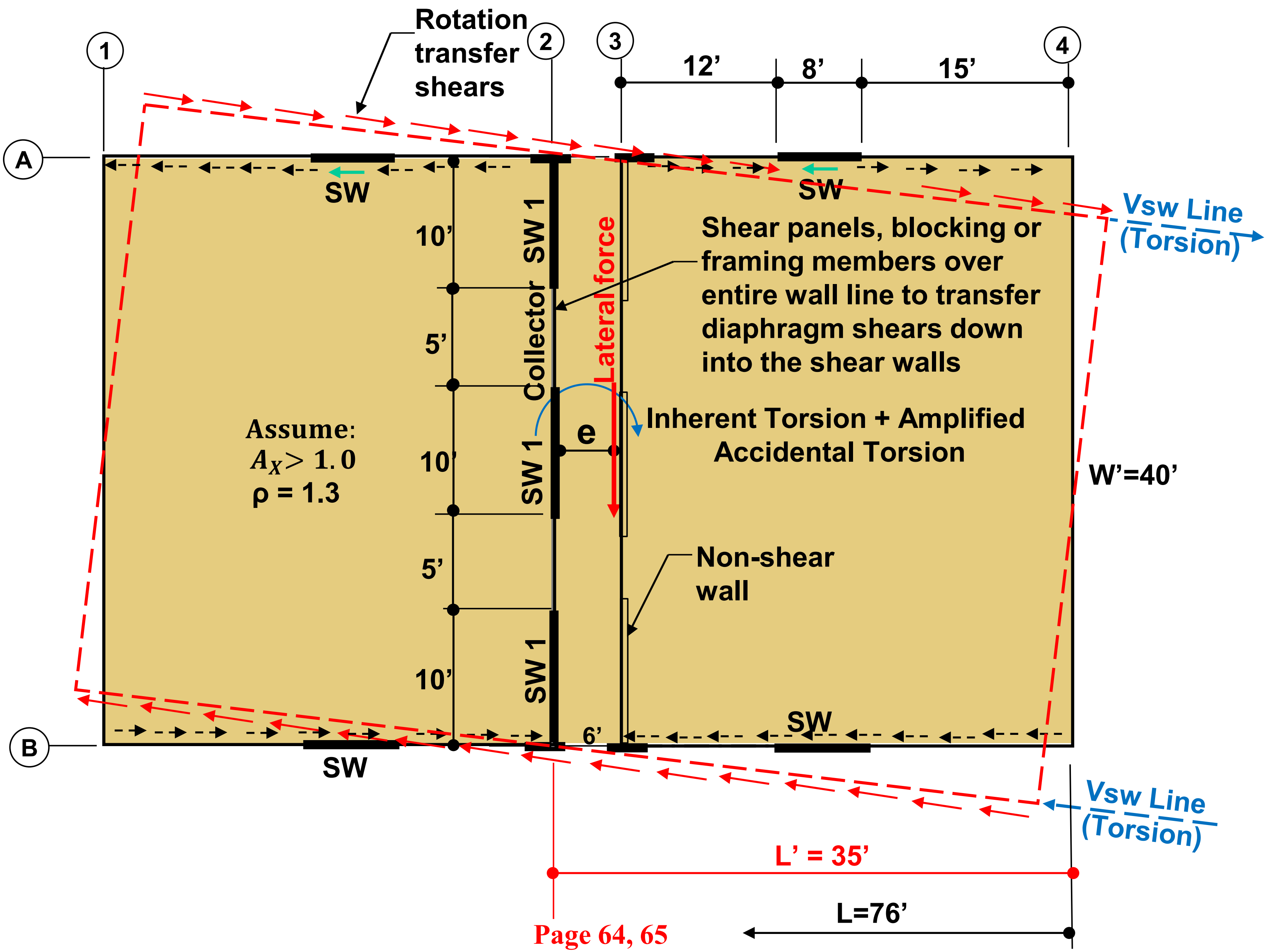
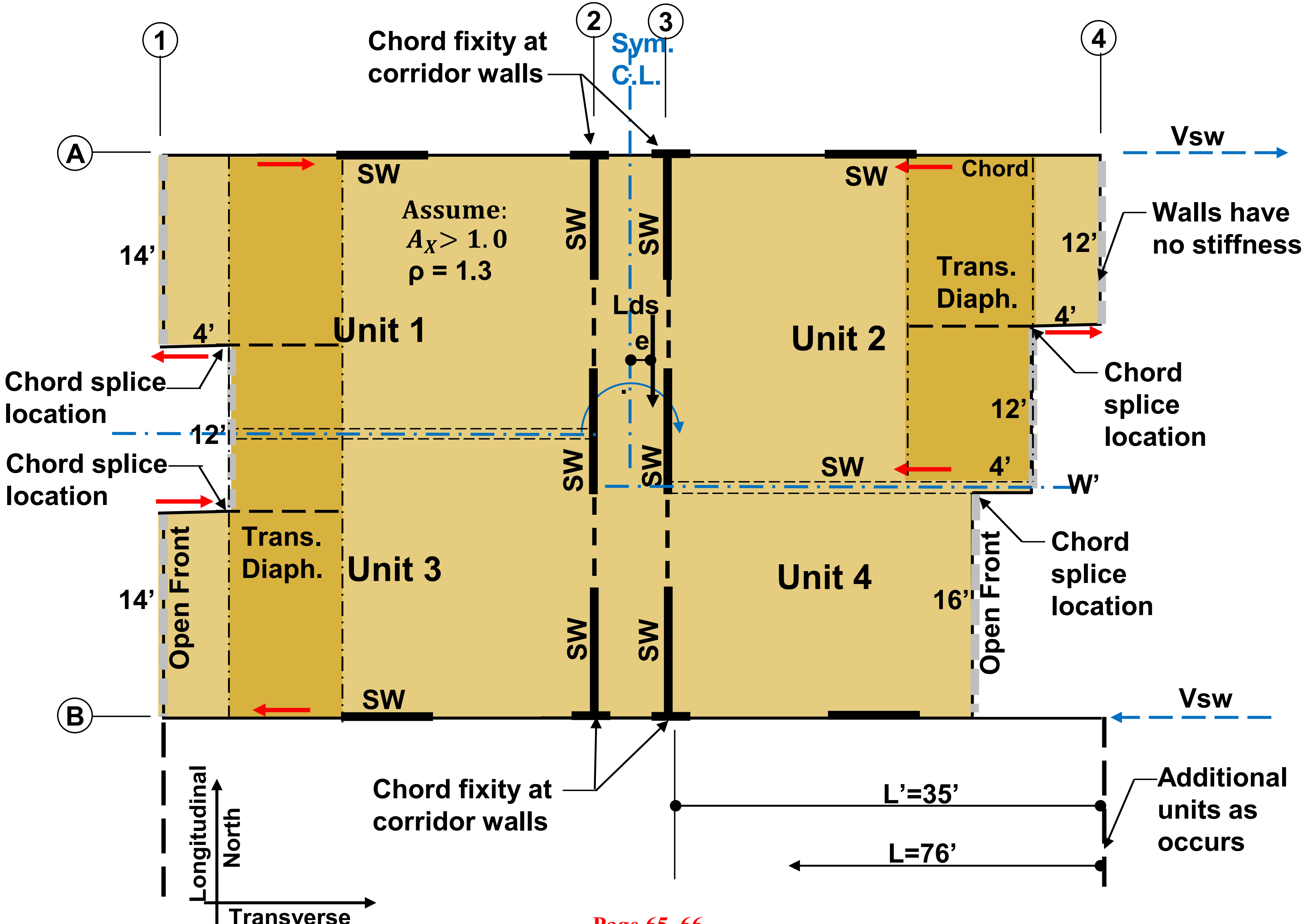
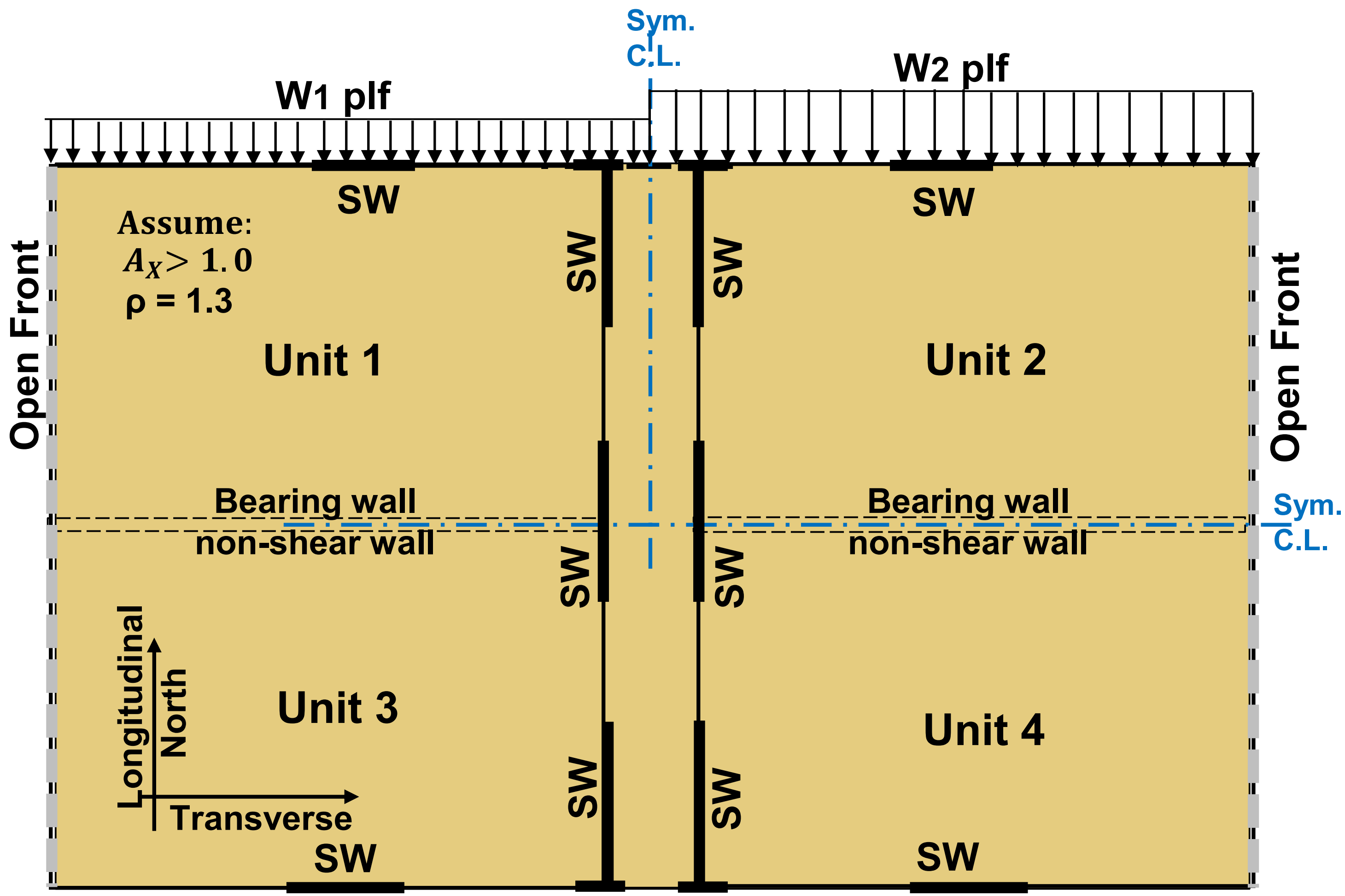
Questionable Plans-Corridor Walls One Side Only



Questionable Plans-Complex Plans-horizontal offsets

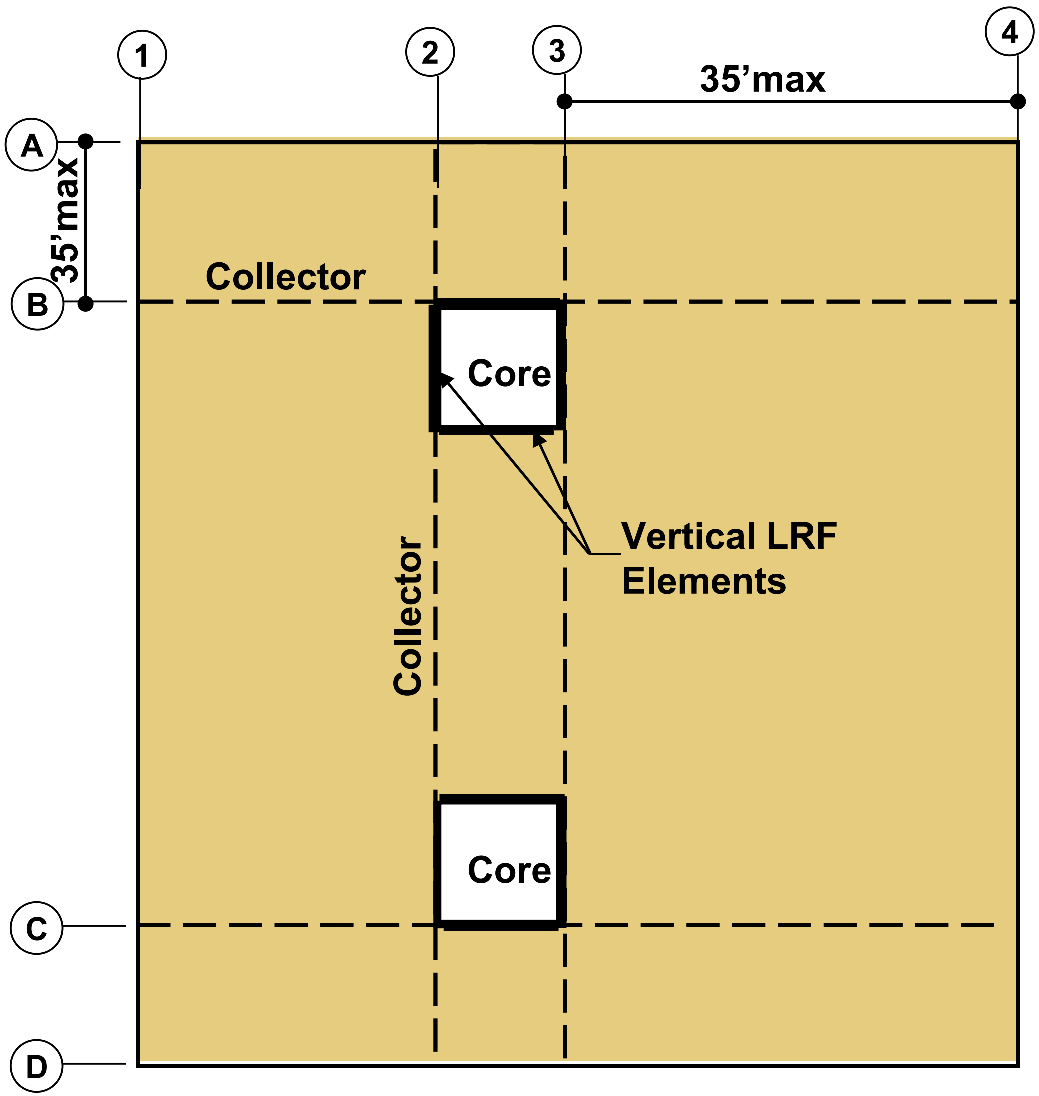


Questionable Plans-Design Example



Questionable Plans-Core Structures

- Can be simple-symmetrical
- Can be complex-different eccentricities



- Light framed
- CLT

2. Diaphragm Flexibility-12.3.1

NEHRP Seismic Design Brief 10 and ASCE 7-16 commentary-"The diaphragms in most buildings braced by wood light-frame shear walls are semi-rigid".

- **The diaphragm stiffness relative to the stiffness of the supporting vertical seismic force-resisting system is important to define.**

ASCE 7, 12.3.1.1 Flexible Diaphragm Condition is allowed provided:

- **All light framed construction**
- **1 ½"or less of non-structural concrete topping**
- **Each line of LFRS is less than or equal to allowable story drift**

Compliance with story drift limits along each line of shearwalls is intended as an indicator that the shearwalls are substantial enough to share load on a tributary area basis and do not require torsional force redistribution.

3. <u>Redundancy</u>

Assume ρ=1.3 unless conditions of ASCE 7-16 Section 12.3.4.2 are met to justify ρ=1.0.

4. <u>Accidental Torsion</u> 12.8.4.2

Accidental torsion shall be applied to all structures for determination <u>if a horizontal irregularity exists</u> as specified in Table 12.3-1.

- **Applies to non-flexible diaphragms**
- **Design shall include the inherent torsional moment (Mt) plus the accidental torsional moments (Mta)**
- **Accidental torsional moment (Mta) = assumed displacement of the C.M. equal to 5% of the dimension of the structure perpendicular to the direction of the applied forces.**

5. Accidental Torsion 12.8.4.2 (Cont.)

Accidental torsion moments (Mta) need not be included when determining:

- **Seismic forces E in the design of the structure, or**
- **Determination of the design story drift in Sections 12.8.6, 12.9.1.2, Chapter 16, or drift limits of Section 12.12.1.**

Exceptions:

- **Structures assigned to Seismic Category B with Type 1b horizontal structural irregularity.**
- **Structures assigned to Seismic Category C, D, E, and F with Type 1a or Type 1b horizontal structural irregularity.**

Structures assigned to SDC C, D, E, or F, where Type 1a or 1b torsional irregularity shall have the effects accounted for by multiplying Mta at each level by a torsional amplification factor (Ax)

For our example, C.M = C.R. No inherent torsion. Only accidental torsion is applied.

Questions?

This concludes Woodworks Presentation on:

Part 1-Code Requirements and Relative Stiffness issues

Your comments and suggestions are valued. They will make a difference.

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Thank You

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