Chapter 7 – Part 1
Horizontal Diaphragm Design

2020 NEHRP Provisions Training Materials

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What's New in Diaphragm Design Provisions

- ASCE/SEI 7-10
  - Sections 12.10.1 and 12.10.2 - *Traditional Diaphragm Design Method*
- ASCE/SEI 7-16 (2015 *NEHRP Provisions*)
  - Section 12.10.3 - *Alternative Design Provisions* is added
    - Cast-in-place concrete, precast concrete, and wood structural panel diaphragms
- ASCE/SEI 7-22 (2020 *NEHRP Provisions*)
  - Section 12.10.3 – *Alternative Design Provisions* is expanded
    - Bare steel deck, concrete-filled steel deck diaphragms
  - Section 12.10.4 – *Alternative RWFD Provisions* is added

What’s New in Diaphragm Design Provisions

- ASCE/SEI 7-16 (2015 *NEHRP Provisions*)
  - Definition of diaphragm transfer forces
  - Amplification of transfer forces by Ω_0 for horizontal structural irregularity type 4
- ASCE/SEI 7-22 (2020 *NEHRP Provisions*)
  - Introduction of special seismic detailing provisions for bare steel deck diaphragms
  - Differentiation of design provisions for diaphragms meeting or not meeting the special seismic detailing provisions

Why Are Diaphragm Design Provisions Changing?

- Driven by research including both testing and numerical studies
- To better reflect diaphragm dynamic response
- To better reflect diaphragm deformation capacity
- Thought to provide better diaphragm performance at the same or potentially lower cost
- More detail later…

Diaphragm Design Presentation Outline – Part 1

- What's new in 2020 *NEHRP Provisions* and ASCE/SEI 7-22
- Overview of horizontal diaphragm design
- Diaphragm seismic design methods
- Example multi-story steel building with steel deck diaphragms
  - Section 12.10.1 and 12.10.2 ***Traditional Design Method***
  - Section 12.10.3 ***Alternative Design Method***
  - *Comparison of results*

Diaphragm Design Presentation Outline – Part 2

- Example one-story RWFD building with steel deck diaphragm
  - Section 12.10.1 and 12.102 ***Traditional Design Method***
  - Section 12.10.4 ***Alternative RWFD Design Method***
  - Comparison of results

Overview of Diaphragm Design

Overview of Diaphragm Design

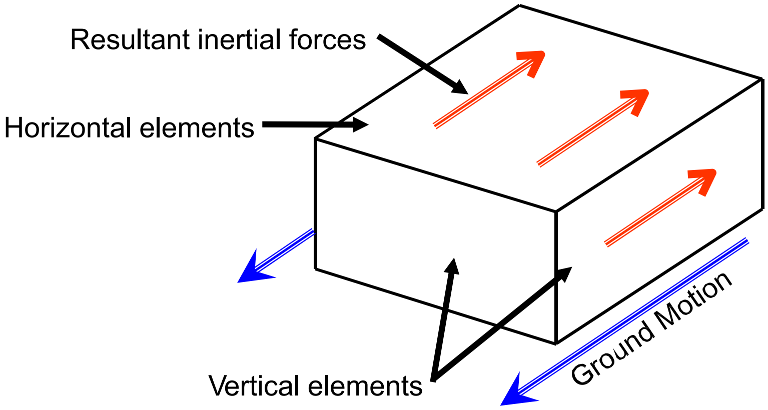
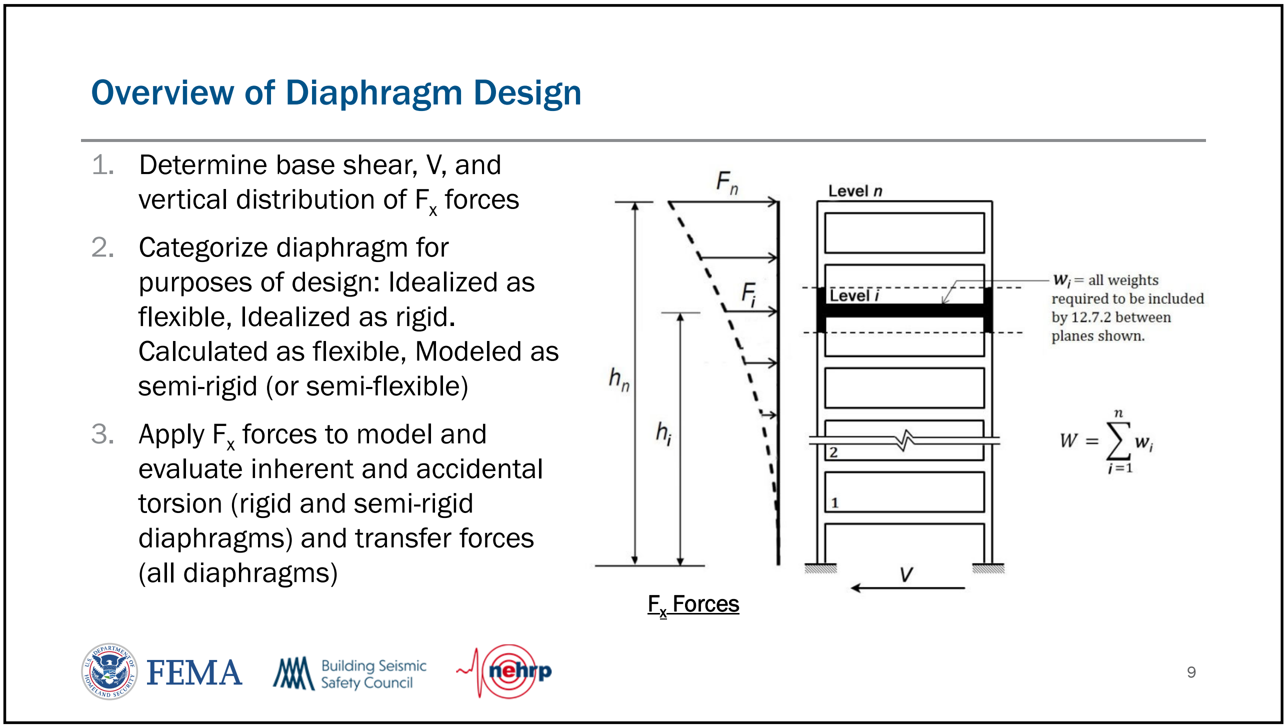


Figure Credit: FEMA, FEMA P-1052 (2016)

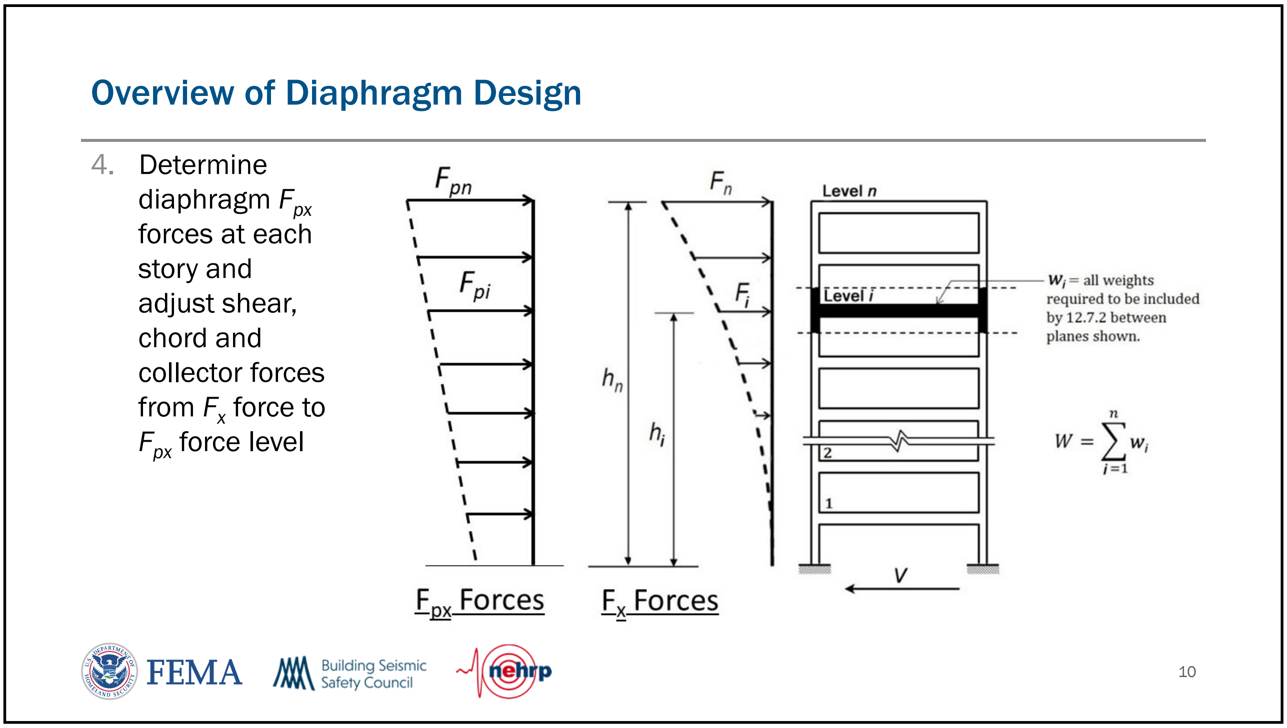


Overview of Diaphragm Design

1. Determine base shear, V, and vertical distribution of F_x forces
2. Categorize diaphragm for purposes of design: Idealized as flexible, Idealized as rigid. Calculated as flexible, Modeled as semi-rigid (or semi-flexible)
3. Apply F_x forces to model and evaluate inherent and accidental torsion (rigid and semi-rigid diaphragms) and transfer forces (all diaphragms)

w_i = all weights required to be included by 12.7.2 between planes shown.

$$W = \sum_{i=1}^{n} w_i$$



Overview of Diaphragm Design

4. Determine diaphragm F_{px} forces at each story and adjust shear, chord and collector forces from F_x force to F_{px} force level

w_i = all weights required to be included by 12.7.2 between planes shown.

$$W = \sum_{i=1}^{n} w_i$$

Overview of Diaphragm Design

5. Design diaphragm for shear and flexure
    - ☐ Adjust diaphragm transfer forces to overstrength level (at horizontal structural irregularity Type 4 only)
6. Design diaphragm chords, collectors, collector connections to vertical elements
    - ☐ Adjust collector forces to overstrength level where applicable
7. Check deflection or drift provisions as applicable

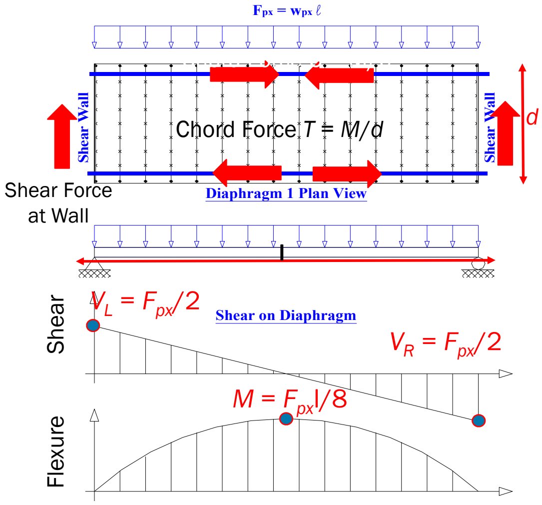
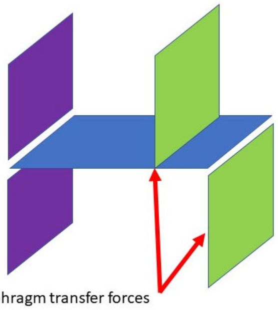


Figure Credit: FEMA, FEMA P-1052 (2016)

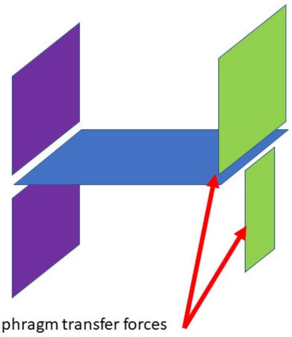
Overview of Diaphragm Design – Transfer Forces

ASCE/SEI 7-22 Section 11.2:

- Transfer Forces, Diaphragm: Forces that occur in a diaphragm caused by transfer of seismic forces from the vertical seismic force-resisting elements above the diaphragm to other vertical seismic force-resisting elements below the diaphragm because of offsets in the placement of the vertical elements or changes in the relative stiffness of the vertical elements.



Diaphragm transfer forces result from offset between shear wall above diaphragm and shear wall below diaphragm



Diaphragm transfer forces result from shear wall reduced stiffness at lower story

Overview of Diaphragm Design - NEHRP Diaphragm Tech Briefs

NIST, NEHRP Seismic Design Technical Brief No. 3, Seismic Design of Cast-in-Place Concrete Diaphragms, Chords and Collectors (2016)

NIST, NEHRP Seismic Design Technical Brief No. 5, Seismic Design of Composite Steel Deck and Concrete-filled Diaphragms (2011)

NIST, NEHRP Seismic Design Technical Brief No. 10, Seismic Design of Wood Light-Frame Structural Diaphragms (2014)

Overview of Diaphragm Design - NEHRP Diaphragm Tech Briefs

- NIST, 2011. *NEHRP Seismic Design Technical Brief No. 5, Seismic Design of Composite Steel Deck and Concrete-filled Diaphragms* (NIST GRC 11-917-10), National Institute of Standards and Technology, Gaithersburg, MD.
- NIST, 2014. *NEHRP Seismic Design Technical Brief No. 10, Seismic Design of Wood Light-Frame Structural Diaphragm Systems* (NIST GRC 14-917-32), National Institute of Standards and Technology, Gaithersburg, MD.
- NIST, 2016a. *NEHRP Seismic Design Technical Brief No. 12, Seismic Design of Cold-Formed Steel Lateral Load-Resisting Systems* (NIST GRC 16-917-38), National Institute of Standards and Technology, Gaithersburg, MD.
- NIST, 2016b. *NEHRP Seismic Design Technical Brief No. 3, Seismic Design of Cast-in-Place Concrete Diaphragms, Chords and Collectors, Second Edition* (NIST GRC 16-917-42), National Institute of Standards and Technology, Gaithersburg, MD.
- NIST, 2017. *NEHRP Seismic Design Technical Brief No. 12, Seismic Design of Precast Concrete Diaphragms* (NIST GRC 17-917-47), National Institute of Standards and Technology, Gaithersburg, MD.

Diaphragm Seismic Design Methods

ASCE/SEI 7-22

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Diaphragm Seismic Design Methods

1. Section 12.10.1 and 12.10.2 ***Traditional Design Method***
2. Section 12.10.3 ***Alternative Design Method***
3. Section 12.10.4 ***Alternative "RWFD" Design Method***:
    - *Alternative Diaphragm Design Provisions for One-Story Structures with Flexible Diaphragms and Rigid Vertical Elements*

- Scope: Diaphragms, Chords and Collectors
    - Design forces
    - In some instances, detailing

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Diaphragm Seismic Design Methods

Method and ASCE/SEI 7-22 Section	Number of Stories Permitted	Diaphragm Systems Included	Comments
Traditional Sections 12.10.1 and 12.10.2	Any	All	▪ Not permitted for precast concrete diaphragms in SDC C through F ▪ Diaphragm design forces are determined using seismic design parameters (R, Ω_0, and C_d) for the vertical SFRS

Diaphragm Seismic Design Methods

Method and ASCE/SEI 7-22 Section	Number of Stories Permitted	Diaphragm Systems Included	Comments
Alternative Section 12.10.3	Any	▪ Cast-in-place concrete ▪ Precast concrete ▪ Wood structural panel ▪ Bare steel deck ▪ Concrete-filled metal deck	▪ Required for precast concrete diaphragms in SDC C through F, providing improved seismic performance ▪ Optional for other diaphragm types ▪ Better reflects vertical distribution of diaphragm forces ▪ R_s diaphragm design force reduction factor better reflects effect of diaphragm ductility and displacement capacity on diaphragm seismic forces ▪ Forces in collectors and their connections to vertical elements are amplified by 1.5 in place of Ω_0

Diaphragm Seismic Design Methods

Method and ASCE/SEI 7-22 Section	Number of Stories Permitted	Diaphragm Systems Included	Comments
Alternative RWFD Section 12.10.4	One Story	▪ Wood structural panel ▪ Bare steel deck ▪ Diaphragm must meet scoping limitations of ASCE/SEI 7-22 Section 12.10.4.1	▪ Primarily intended for buildings with diaphragm spans of 100 feet or greater ▪ New T_{diaph}, R_{diaph}, $\Omega_{0\text{-diaph}}$, and $C_{d\text{-diaph}}$, better reflect response of RWFD building type ▪ Provides better performance with the same or reduced construction cost

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Diaphragm Seismic Design Methods

- Advantages of using Section 12.10.3 Alternative Design Provisions:
  - Better reflects vertical distribution of diaphragm forces
  - Better reflects effect of diaphragm ductility and displacement capacity
  - May result in lower seismic demands
- Advantages of using Section 12.10.4 Alternative RWFD Method;
  - Better reflects seismic response of RWFD buildings
  - May result in lower seismic demands
  - Is anticipated to result in better performance
- When will the Section 12.10.1 and 12.10.2 Traditional Method result in lower design forces?
  - Bare steel deck diaphragms not meeting the AISI S400 special seismic detailing provisions
  - Other

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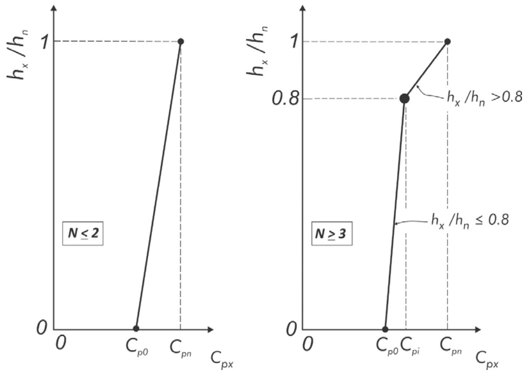
Introduction to Section 12.10.3 Alternative Design Provisions

Part 1: Vertical distribution of seismic forces for near-elastic diaphragm behavior



Part 2: Parameter R_s modifies near-elastic forces based on diaphragm ductility and deformation capacity

$$F_{px} = \frac{C_{px}}{R_s} w_{px}$$

Introduction to Section 12.10.3 Alternative Design Provisions

Studies Behind Alternative Provisions Diaphragm Forces and Tabulated R_s factors:

- Precast concrete diaphragms
  - Fleischman R.B., Restrepo J.I, Naito C.J., Sause R., Zhang D. and Schoettler M., 2013. “Integrated Analytical and Experimental Research to Develop a New Seismic Design Methodology for Precast Concrete Diaphragms,” *ASCE J. Struct. Engr*., 139(7), 1192-1204.
  - 2020 *NEHRP Provisions* Commentary
- Concrete diaphragms - 2020 *NEHRP Provisions* Commentary
- Wood structural panel diaphragms – 2020 *NEHRP Provisions* Commentary

Introduction to Section 12.10.3 Alternative Design Provisions

Studies Behind Tabulated R_s factors:

- Bare steel deck diaphragms and concrete filled metal deck diaphragms
  - O'Brien, P., Eatherton, M.R., and Easterling, W.S., 2017. "Characterizing the Load-Deformation Behavior of Steel Deck Diaphragms using Past Test Data," Cold-Formed Steel Research Consortium Report Series, CFSRC R-2017-02
  - Schafer, 2019. *Research on the Seismic Performance of Rigid Wall Flexible Diaphragm Buildings with Bare Steel Deck Diaphragms*, CFSRC Report 2019-2.
  - Wei, G., Foroughi, H., Torabian, S., Schafer, B.W., and Eatherton, M.R., 2019. "Evaluating Different Diaphragm Design Procedures Using Nonlinear 3D Computational Models," 12th Canadian Conference on Earthquake Engineering, Quebec QC, June 17-20
  - Avellaneda, R.E., Easterling, W.S., Schafer, B.W., Hajjar, J.F., and Eatherton, M.R., 2019. "Cyclic Testing of Composite Concrete on Metal Deck Diaphragms Undergoing Diagonal Tension Cracking," 12th Canadian Conference on Earthquake Engineering, Quebec QC, June 17-20.
  - Foroughi, H., Wei, G., Torabian, S., Eatherton, M.R., and Schafer, B.W., 2019. "Seismic Demands on Steel Diaphragms for 3D Archetype Buildings with Concentric Braced Frames," 12th Canadian Conference on Earthquake Engineering, Quebec QC, June 17-20

Introduction to Section 12.10.3 Alternative Design Provisions – Part 1

3-Story PCI Building – test results

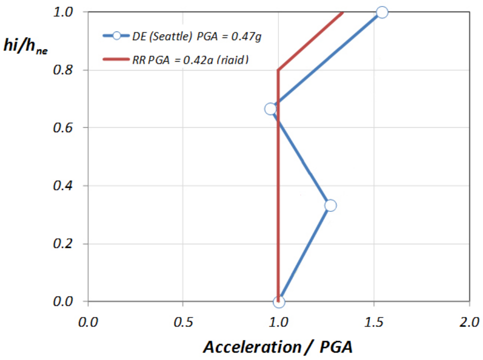


Figure Credit: FEMA, FEMA P-1052 (2016) Courtesy of Jose Restrepo, UC San Diego

Steel BRB and special MRF buildings - analysis

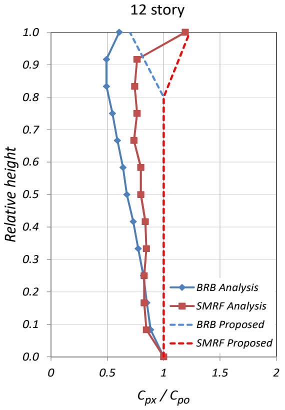


Figure Credit: FEMA, FEMA P-1052, (2016) Courtesy of Jose Restrepo, UC San Diego

Introduction to Section 12.10.3 Alternative Design Provisions – Part 2

Diaphragm System		R_s - Shear-Controlled[a]	R_s - Flexure-Controlled[a]
Cast-in-place concrete designed in accordance with ACI 318	-	1.5	2
Precast concrete designed in accordance with ACI 318	Elastic design option	0.7	0.7
	Basic design option	1.0	1.0
	Reduced design option	1.4	1.4
Wood sheathed designed in accordance with ASCE/SEI 7-22 Section 14.5 and *AWC Special Design Provisions for Wind and Seismic*	-	3.0	NA
Bare steel deck designed in accordance with ASCE/SEI 7-22 Section 14.1.5	With special seismic detailing	2.5	NA
	Other	1.0	NA
Concrete-filled metal deck designed in accordance with ASCE/SEI 7-22 Section 14.1.6	-	2.0	NA

Introduction to Section 12.10.4 Alternative RWFD Design Method

Acknowledge and incorporate actual seismic response of RWFD buildings for diaphragm design

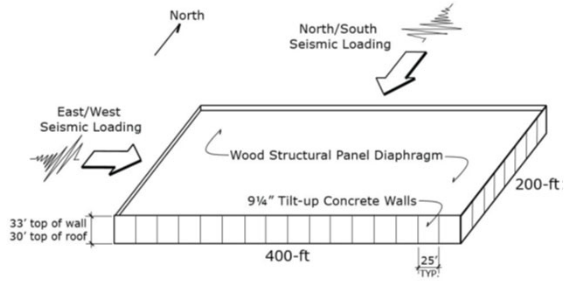
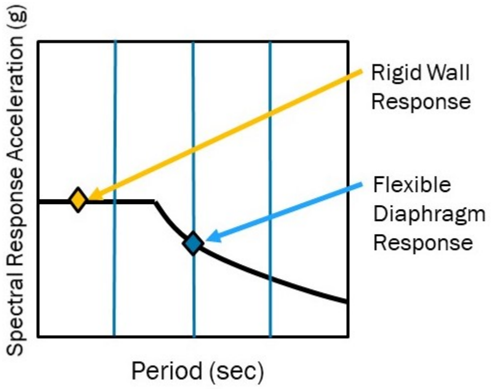


Figure Credit: FEMA, FEMA P-1026 (2014)



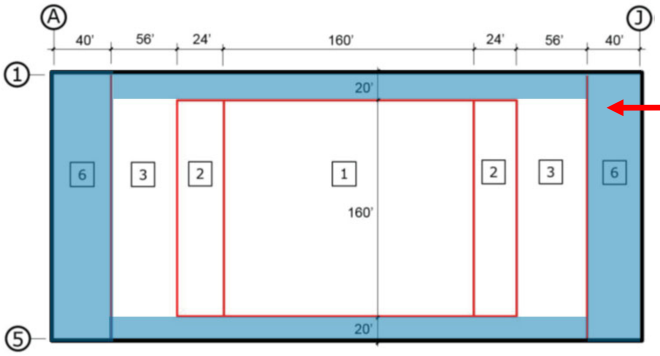
Introduction to Section 12.10.4 Alternative RWFD Design Method

Studies Behind Alternative RWFD Design Method:

- FEMA, 2021. *Seismic Design of Rigid Wall-Flexible Diaphragm Buildings: An Alternate Procedure* (FEMA P-1026), Federal Emergency Management Agency, Washington, DC
- Koliou, M., Filiatrault, A., Kelly, D., and Lawson, J., 2015a. “Buildings with Rigid Walls and Flexible Diaphragms I: Evaluation of Current U.S. Seismic Provisions,” *Journal of Structural Engineering*, American Society of Civil Engineers, Reston, VA.
- Koliou, M., Filiatrault, A., Kelly, D., and Lawson, J., 2015b. “Buildings with Rigid Walls and Flexible Diaphragms II: Evaluation of a New Seismic Design Approach Based on Distributed Diaphragm Yielding,” *Journal of Structural Engineering*, American Society of Civil Engineers, Reston, VA.
- Schafer, 2019. *Research on the Seismic Performance of Rigid Wall Flexible Diaphragm Buildings with Bare Steel Deck Diaphragms*, CFSRC Report 2019-2.

Introduction to Section 12.10.4 Alternative RWFD Design Method

Design to encourage distributed inelastic behavior for improved seismic performance

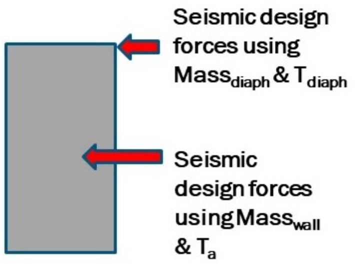


Amplified Shear Boundary Zone

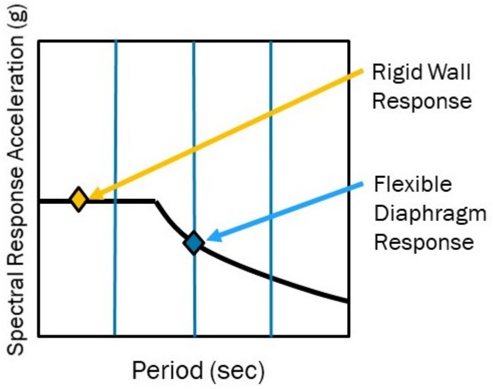
Figure Based on FEMA, FEMA P-1026 (2014)

Introduction to Section 12.10.4 Alternative RWFD Design Method

Optional incorporation of actual seismic response of RWFD buildings for vertical elements – 2 stage analysis

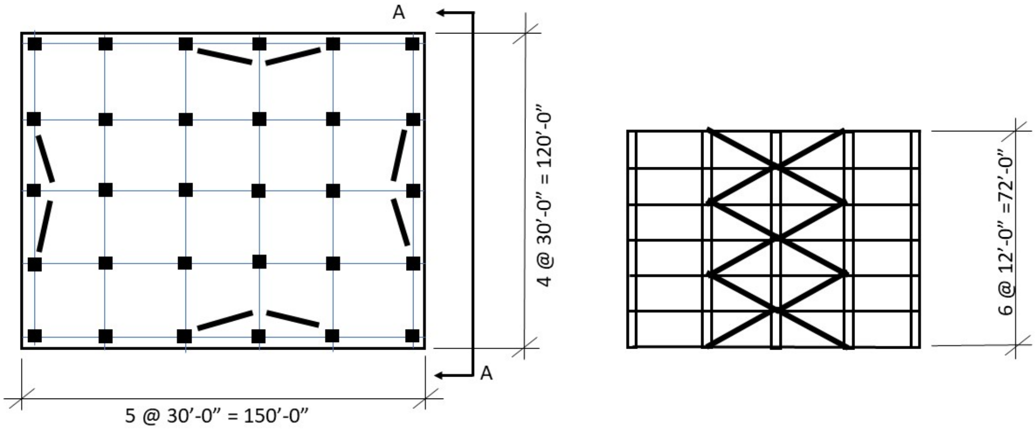


Seismic Design Forces to Vertical Element



Example Multi-Story Steel Building with Steel Deck Diaphragms

Example Multi-Story Steel Building with Steel Deck Diaphragms



Floor Plan

Elevation AA

Example Multi-Story Steel Building with Steel Deck Diaphragms

Building Configuration

- Six stories
- Risk Category II, I_e = 1.0
- Mean roof height = 72 feet - six stories at 12 feet each
- Length = 150 feet
- Width = 120 feet
- S_{DS} = 1.2, S_{D1} = 0.70 (determined using ASCE/SEI 7-22 Section 11.4.4)
- Floor Diaphragm: Concrete-filled metal deck
- Roof Diaphragm: Bare steel deck
- Steel special concentrically braced frame system - R= 6, Ω_0= 2
- Rho, ρ, = 1.0 for both vertical elements and diaphragm
- All seismic forces are at strength level

Example Multi-Story Steel Building with Steel Deck Diaphragms

Building Analytical Modeling

- The step-by-step descriptions in this presentation focus on use of the ASCE/SEI 7-22 equivalent lateral force (ELF) procedure; some modifications are needed when using linear dynamic analysis procedures.
- This step-by-step description also focuses primarily on diaphragm inertial forces due to the mass tributary to each diaphragm level. Where diaphragm transfer forces as defined in ASCE/SEI Section 11.2 occur, they are required to be addressed in accordance with ASCE/SEI 7-22 Section 12.10.1.1 or 12.10.3.3, as applicable.

Example Multi-Story Steel Building with Steel Deck Diaphragms

Building Analytical Modeling (continued)

- In order to perform seismic analysis of the SFRS and diaphragms, it is necessary to define the diaphragm flexibility in accordance with ASCE/SEI 7-22 Section 12.3. This section sets criteria by which diaphragms can be idealized as flexible, idealized as rigid, or calculated as flexible. Where these do not apply, the diaphragm is required to be modeled as semi-rigid.
- Where diaphragms are designated as rigid or semi-rigid for modeling and design, the process of seismic design will start with overall modeling of the building and then proceed to diaphragm design. Regardless of diaphragm designation, the seismic design of the diaphragm and vertical elements usually proceed in parallel.

Example Multi-Story Steel Building with Steel Deck Diaphragms

Step 1 - Weight for Seismic Analysis

- Roof + ceiling = 40 psf
- Floor + ceiling = 80 psf
- Exterior wall = 20 psf
- Interior partitions are included as 10 psf in floor + ceiling weight of 80 psf

Example Multi-Story Steel Building with Steel Deck Diaphragms

Step 1 - Seismic weight at roof

Roof: 40 psf (150 ft)(120 ft) = 720 kips

Longitudinal exterior walls: 20 psf (150 ft)(12/2 + 4 ft)(2 sides) = 60 kips

Transverse exterior walls: 20 psf (120 ft)(12/2 + 4 ft)(2 sides) = 48 kips

TOTAL = 720 + 60 + 48
= 828 kips acting at roof

Example Multi-Story Steel Building with Steel Deck Diaphragms

Step1 - Seismic weight at 2nd through 6th floors

Floor: 80 psf (150 ft)(120 ft) = 1440 kips

Longitudinal exterior wall: 20 psf (150 ft)(12 ft)(2 sides) = 72 kips

Transverse exterior wall: 20 psf (120 ft)(12 ft)(2 sides) = 58 kips

TOTAL = 1440 + 72 + 58

= 1,570 kips   acting at each floor

Seismic weight TOTAL = 828 + 5 (1,570) = 8,678 kips

Example Multi-Story Steel Building with Steel Deck Diaphragms

Step 1 - Diaphragm seismic weight, w_{px}, at the roof:

= 828 kips (transverse and longitudinal directions)

Step 1- Diaphragm seismic weight, w_{px}, at the 2nd through 6th floors:

= 1,570 kips (transverse and longitudinal direction)

Diaphragm seismic weights with exterior wall weight parallel to the direction of seismic forces neglected are between 4 and 8 percent lower than total seismic weight. These forces are not carried by the diaphragm but instead act directly at the vertical elements. For simplicity, however, use total seismic weights of 828 and 1,570 kips to determine diaphragm design forces.

Example Multi-Story Steel Building with Steel Deck Diaphragms

Step 2 - ASCE 7 Base Shear

$T_a = C_t h_n^x = 0.020(72)^{0.75}$ =0.49 sec (ASCE/SEI 7-22 Eq. 12.8-7)

$\boldsymbol{C_s} = \frac{S_{DS}}{\frac{R}{I_e}} = \frac{1.20}{\frac{6}{1}}$ =0.200 (governs) (ASCE/SEI 7-22 Eq. 12.8-2)

C_s need not exceed:

$\boldsymbol{C_s} = \frac{S_{D1}}{T\left(\frac{R}{I_e}\right)} = \frac{0.70}{0.49\left(\frac{6}{1}\right)}$ =0.238 (ASCE/SEI 7-22 Eq. 12.8-3)

$V = C_s W$ = 0.20 (8,678) = 1,736 kips (ASCE/SEI 7-22 Eq. 12.8-1)

Example Multi-Story Steel Building with Steel Deck Diaphragms

Step 3 - Vertical distribution of seismic base shear:

The lateral seismic force at any level is determined as

$F_x = C_{vx} V$ (ASCE/SEI 7-22 Eq. 12.8-11)

Where:

$C_{vx} = \frac{w_x h_x^k}{\sum_{i=1}^{n} w_i h_i^k}$ (ASCE/SEI 7-22 Eq. 12.8-12)

For $T \leq 0.5$ sec., $k = 1.0$

Example Multi-Story Steel Building with Steel Deck Diaphragms

Table 7.5-1: Vertical Distribution of Base Shear

Level X	w_x (kips)	h_x (ft)	$w_x h_x^k$ (ft-kips)	C_{vx}	F_x (kips)
Roof	828	72	59,616	0.174	302
6	1,570	60	94,200	0.275	478
5	1,570	48	75,360	0.220	382
4	1,570	36	56,520	0.165	287
3	1,570	24	37,680	0.110	191
2	1,570	12	18,840	0.055	96
Sum	8,678		342,216	0.999	1,736

1.0 kip = 4.45 kN, 1.0 ft = 0.3048 m, 1.0 ft-kip = 1.36 kN-m

Example Multi-Story Steel Building with Steel Deck Diaphragms

Traditional Design Method (12.10.1 & 12.10.2)

Traditional Design Method

Step 4 - Strength level diaphragm design force, F_{px}:

Diaphragm design force is given by the larger of F_x determined previously and F_{px}

$$F_{px} = \frac{\sum_{i=x}^{n} F_i}{\sum_{i=x}^{n} w_i} w_{px} \qquad \text{(ASCE/SEI 7-22 Eq. 12.10-1)}$$

Note that for purposes of diaphragm forces ρ is set to 1.0.

Traditional Design Method

Table 7.5-2: Diaphragm Seismic Forces, F_{px}

Level	w_i (kips)	$\sum_{i=x}^{n} w_i$ (kips)	F_i (kips)	$\sum_{i=x}^{n} F_i = V_i$ (kips)	w_{px} (kips)	$F_{px} = \frac{\sum_{i=x}^{n} F_i}{\sum_{i=x}^{n} w_i} w_{px}$ (kips)
Roof	828	828	302	302	828	302
6	1,570	2,398	478	780	1,570	510
5	1,570	3,968	382	1,162	1,570	460
4	1,570	5,538	287	1,449	1,570	411
3	1,570	7,108	191	1,640	1,570	362
2	1,570	8,678	96	1,736	1,570	314
Sum	8,678		1,736		8,678	

1.0 kip = 4.45 kN

Traditional Design Method

F_{px} at the roof cannot be less than:

$F_{pr} = 0.2S_{DS}I_e w_{pr}$ (ASCE/SEI 7-22 Eq. 12.10-2)

$= 0.2(1.2)(1.0)(828) = 199$ kips

F_{px} at the floor levels cannot be less than:

$F_{px} = 0.2S_{DS}I_e w_{px}$ (ASCE/SEI 7-22 Eq. 12.10-2)

$= 0.2(1.2)(1.0)(1{,}570) = 377$ kips

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Traditional Design Method

F_{px} at the roof need not exceed:

$F_{pr} = 0.4S_{DS}I_e w_{pr}$ (ASCE/SEI 7-22 Eq. 12.10-3)

$= 0.4(1.2)(1.0)(828) = 397$ kips

F_{px} at the floor levels need not exceed:

$F_{px} = 0.4S_{DS}I_e w_{px}$ (ASCE/SEI 7-22 Eq. 12.10-3)

$= 0.4(1.2)(1.0)(1{,}570) = 754$ kips

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Traditional Design Method

Table 7.5-3: Summary of Diaphragm Design Forces

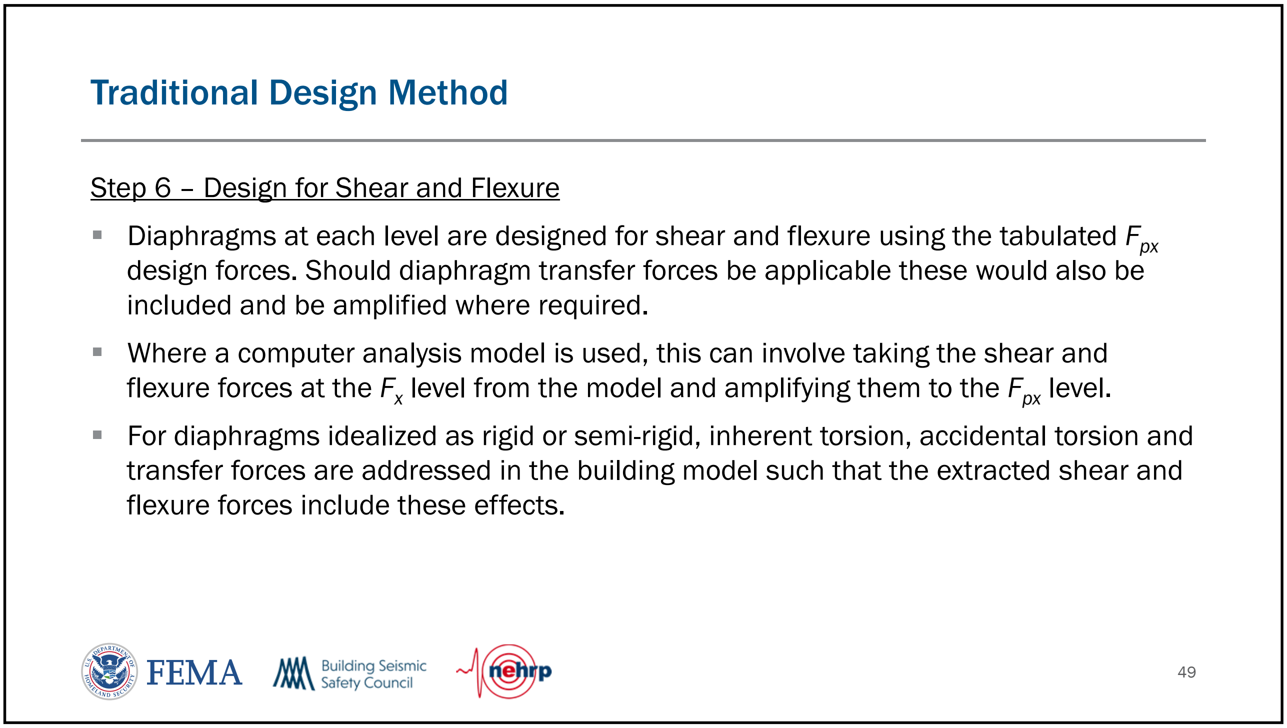
Level	F_{px} From Vertical Distribution (kips)	F_{px} Minimum (kips)	F_{px} Maximum (kips)	F_{px} Design (kips)
Roof	302	199	397	302
6	510	377	754	510
5	460	377	754	460
4	411	377	754	411
3	362	377	754	377
2	314	377	754	377

1.0 kip = 4.45 kN

Traditional Design Method

Step 5 – Diaphragm Transfer Forces

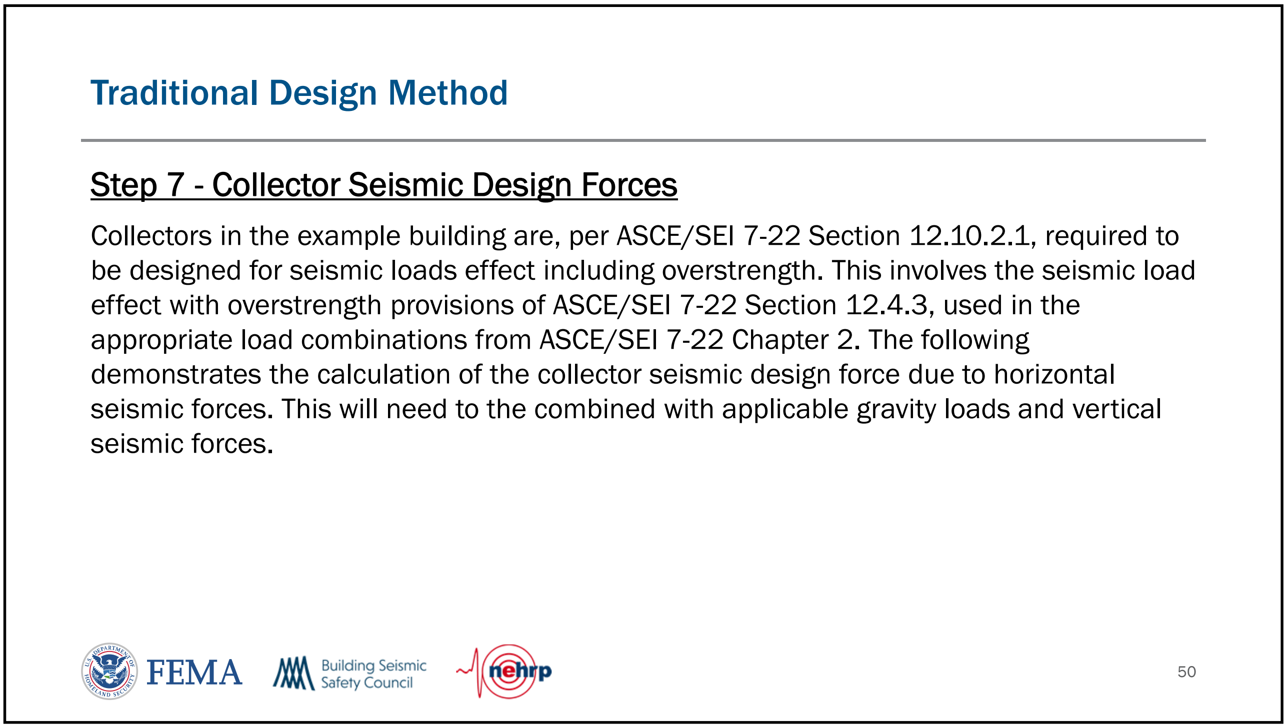
- Diaphragm transfer forces, as defined in ASCE/SEI 7-22 Section 11.2, occur where vertical elements of the SFRS are offset or discontinued at lower levels; they also occur due to changes in the stiffness of the SFRS vertical elements between levels. The occurrence of diaphragm transfer forces is determined by examining the distribution of forces from the analysis model.
- For simplicity, the building in this example building is assumed to not have diaphragm transfer forces.



Traditional Design Method

Step 6 – Design for Shear and Flexure

- Diaphragms at each level are designed for shear and flexure using the tabulated F_{px} design forces. Should diaphragm transfer forces be applicable these would also be included and be amplified where required.
- Where a computer analysis model is used, this can involve taking the shear and flexure forces at the F_x level from the model and amplifying them to the F_{px} level.
- For diaphragms idealized as rigid or semi-rigid, inherent torsion, accidental torsion and transfer forces are addressed in the building model such that the extracted shear and flexure forces include these effects.

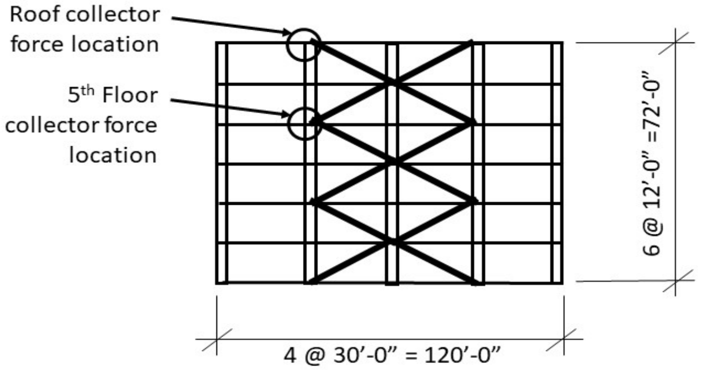


Traditional Design Method

Step 7 - Collector Seismic Design Forces

Collectors in the example building are, per ASCE/SEI 7-22 Section 12.10.2.1, required to be designed for seismic loads effect including overstrength. This involves the seismic load effect with overstrength provisions of ASCE/SEI 7-22 Section 12.4.3, used in the appropriate load combinations from ASCE/SEI 7-22 Chapter 2. The following demonstrates the calculation of the collector seismic design force due to horizontal seismic forces. This will need to the combined with applicable gravity loads and vertical seismic forces.

Traditional Design Method



Elevation AA

Traditional Design Method

Step 7 - Diaphragm Transverse Force Reactions and Units Shears

The roof diaphragm is idealized to be flexible. As a result, the diaphragm reaction to the exterior wall line can be based on tributary seismic weight or a simple-span beam idealization. Based on this assumption:

Roof Diaphragm V = 302 kips /2 = 151 kips

(Flexible Diaphragm) v = 151 kips / 120 ft = 1.26 klf

Traditional Design Method

Step 7 - Diaphragm Transverse Force Reactions and Units Shears

For this example, the floor diaphragms are idealized as rigid. As a result, inherent and accidental torsion are applied to the model seismic forces in accordance with Sec. 12.8.4. In this example it is assumed a 10% increase of the floor diaphragm shear due to torsion and any transfer forces. Based on this assumption:

5th Floor diaphragm	V = 460 kips (1.1*)/ 2 = 253 kips
(Rigid Diaphragm)	v = 253 kips / 120 ft = 2.11 klf

* Extracted from building analysis, value will vary

Traditional Design Method

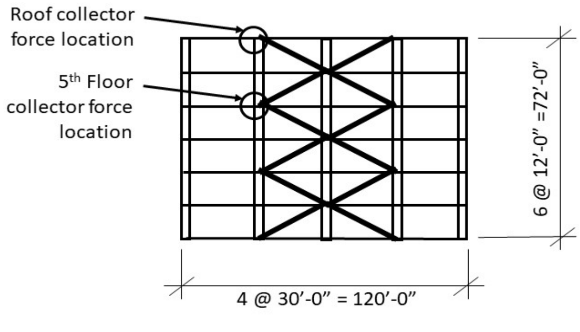
Step 7 - Collector Force at Location shown in Figure 7.5-2, amplified by Ω_0 = 2.0

Roof Diaphragm

T/C = 1.26 klf (30 ft) (2.0) = 76 kips

5th Floor Diaphragm

T/C = 2.11 klf (30 ft) (2.0) = 127 kips



Elevation AA

Traditional Design Method

Step 8 – Deflection and Drift Requirements

For ELF design, this step incorporates the revised displacement and drift determination provisions of ASCE/SEI 7-22 Section 12.8.6 and the drift and deformation provisions of Section 12.12.

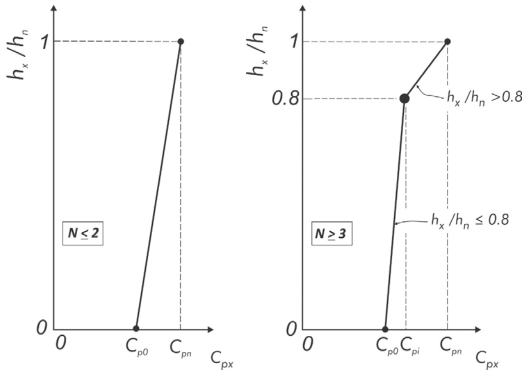
The structural separation provisions of Section 12.12.2, structural separation requirements of Section 12.12.3, and deformation compatibility provisions of 12.12.4 each require that diaphragm deflection be considered in addition to the deflection of the vertical elements.

Example Multi-Story Steel Building with Steel Deck Diaphragms

Alternative Design Method (12.10.3)

Alternative Design Provisions (Section 12.10.3) - Introduction

Part 1: Vertical distribution of seismic forces for near-elastic diaphragm behavior



Part 2: Parameter R_s modifies near-elastic forces based on diaphragm ductility and deformation capacity

$$F_{px} = \frac{C_{px}}{R_s} w_{px}$$

Alternative Design Method (Section 12.10.3) - Introduction

Advantages of using Section 12.10.3 Alternative Design Provisions:

- Better reflects vertical distribution of diaphragm forces
- Better reflects affect of diaphragm ductility and displacement capacity
- May result in lower seismic demands

Example Multi-Story Steel Building with Steel Deck Diaphragms

Table 7.5-1: Vertical Distribution of Base Shear

Level X	w_x (kips)	h_x (ft)	$w_x h_x^k$ (ft-kips)	C_{vx}	F_x (kips)
Roof	828	72	59,616	0.174	302
6	1,570	60	94,200	0.275	478
5	1,570	48	75,360	0.220	382
4	1,570	36	56,520	0.165	287
3	1,570	24	37,680	0.110	191
2	1,570	12	18,840	0.055	96
Sum	8,678		342,216	0.999	1,736

1.0 kip = 4.45 kN, 1.0 ft = 0.3048 m, 1.0 ft-kip = 1.36 kN-m

Alternative Design Method (Section 12.10.3)

NEAR ELASTIC

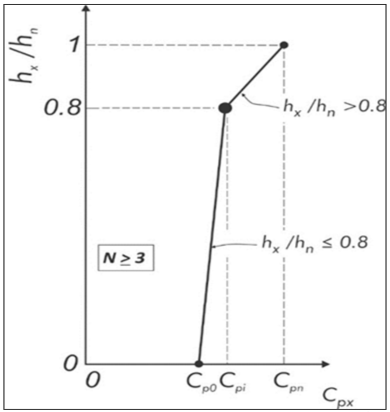
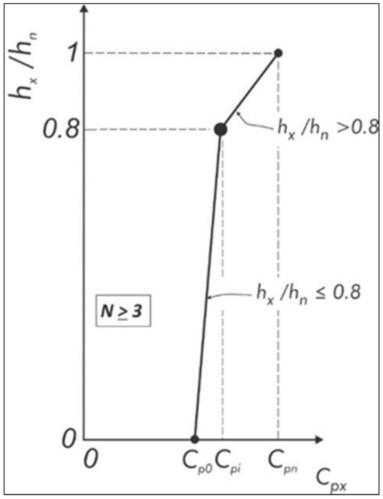


Figure 7.5-3. Calculating the Design Acceleration Coefficient, C_{px}, in Buildings with $N \geq 3$ (ASCE/SEI 7 Figure 12.10-2)

Alternative Design Method (Section 12.10.3)



$N = 6$

$z_s = 1.0$ (all other SFRS, ASCE/SEI 7-22 Section 12.10.3.2.1)

$R_s = 2.0$ for concrete-filled metal deck floor diaphragm (ASCE/SEI 7-22 Table 12.10-1)

$R_s = 1.0$ bare steel deck roof diaphragm with welded connections not meeting special seismic detailing provisions (ASCE/SEI 7-22 Table 12.10-1)

$C_s = 0.200$ (Slide 39)

Alternative Design Method (Section 12.10.3)

ASCE/SEI 7-22 Table 12.10-1 Diaphragm Design Force Reduction Factor, R_s

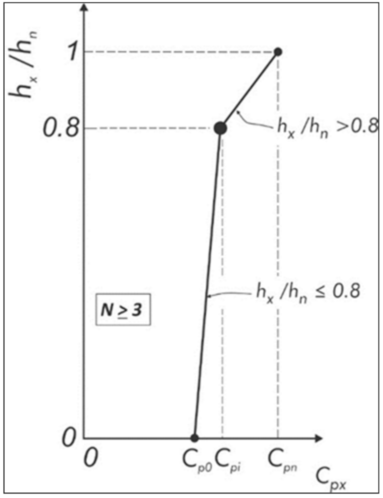
Diaphragm System		Shear-Controlled[a]	Flexure-Controlled[a]
Cast-in-place concrete designed in accordance with ACI 318	-	1.5	2
Precast concrete designed in accordance with ACI 318	Elastic design option	0.7	0.7
	Basic design option	1.0	1.0
	Reduced design option	1.4	1.4
Wood sheathed designed in accordance with ASCE/SEI 7-22 Section 14.5 and *AWC Special Design Provisions for Wind and Seismic*	-	3.0	NA
Bare steel deck designed in accordance with ASCE/SEI 7-22 Section 14.1.5	With special seismic detailing	2.5	NA
	Other	1.0	NA
Concrete-filled steel deck designed in accordance with ASCE/SEI 7-22 Section 14.1.6	-	2.0	NA

Alternative Design Method (Section 12.10.3)

Modal Contribution Coefficient Modifier, z_s *(ASCE/SEI 7-22 Section 12.10.3.2.1)*

Description	z_s value
Buildings designed with Buckling-Restrained Braced Frame systems defined in ASCE/SEI 7-22 Table 12.2-1	0.30
Buildings designed with Moment-Resisting Frame systems defined in ASCE/SEI 7-22 Table 12.2-1	0.70
Buildings designed with Dual Systems defined in ASCE/SEI 7-22 Table 12.2-1 with Special or Intermediate Moment Frames capable of resisting at least 25% of the prescribed seismic forces	0.85
Buildings designed with all other seismic force-resisting systems	1.00

Alternative Design Method (Section 12.10.3)



$N = 6$

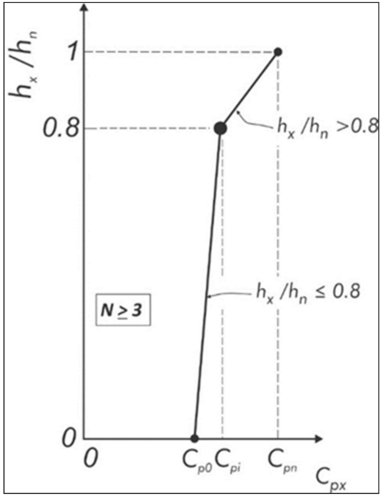
$z_s = 1.0$ (all other SFRS, ASCE/SEI 7-22 Section 12.10.3.2.1)

$R_s = 2.0$ for concrete-filled metal deck floor diaphragm (ASCE/SEI 7-22 Table 12.10-1)

$R_s = 1.0$ bare steel deck roof diaphragm with welded connections not meeting special seismic detailing provisions (ASCE/SEI 7-22 Table 12.10-1)

$C_s = 0.200$ (Slide 39)

Alternative Design Method (Section 12.10.3)



First Mode Contribution Factor

$$\Gamma_{m1} = 1 + 0.5 z_s \left(1 - \frac{1}{N}\right)$$ (Eq. 12.10−13)

$$= 1 + 0.5 \times 1.00 \times \left(1 - \frac{1}{6}\right) = 1.42$$

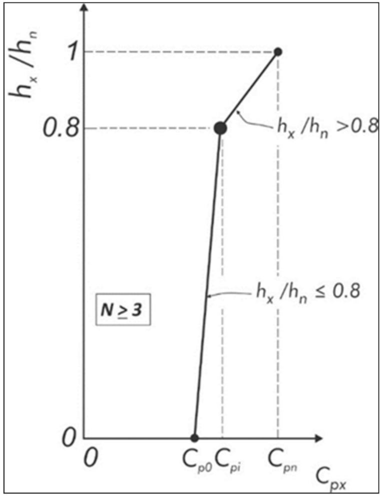
Higher Mode Contribution Factor

$$\Gamma_{m2} = 0.9 z_s \left(1 - \frac{1}{N}\right)^2$$

$$= 0.9 \times 1.00 \times \left(1 - \frac{1}{6}\right)^2$$

$$= .625$$ (Eq. 12.10 – 14)

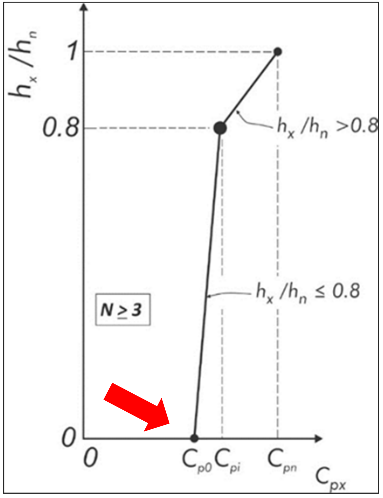
Alternative Design Method (Section 12.10.3)



Higher Mode Response Coefficient C_{s2} is taken as the lesser of the following:

- $C_{s2} = (0.15N + 0.25) I_e S_{DS}$
- $= (0.15 \times 6 + 0.25) \times 1.0 \times 1.2 = 1.38$ (Eq. 12.10−10)
- $C_{s2} = I_e S_{DS} = 1.0 \times 1.2 = 1.2$ (Eq. 12.10−11)
- $C_{s2} = \frac{I_e S_{D1}}{0.03(N-1)} = \frac{1.0 \times 0.7}{0.03\,(6-1)} = 4.7$ (Eq. 12.10−12a)
- Use C_{s2} = 1.2

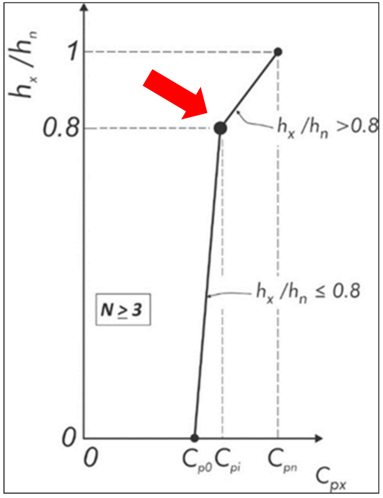
Alternative Design Method (Section 12.10.3)



Diagraphm Design Acceleration Coefficient at the Structure Base

$C_{p0} = 0.4S_{DS}I_e = 0.4(1.2)(1.00) = 0.48$ (Eq 12.10-6}

Alternative Design Method (Section 12.10.3)



Diaphragm Design Acceleration Coefficient at 80% of the Structure Height

C_{pi} is taken as the greater of the following:

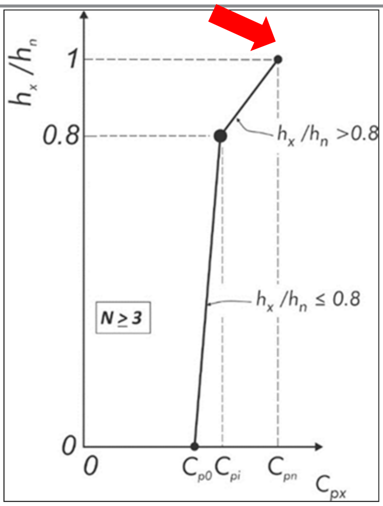
$C_{pi} = C_{p0} = 0.48$ (Eq. 12.10-8)

$C_{pi} = 0.9\Gamma_{m1}\Omega_0 C_s$ (Eq. 12.10 -9)

$= 0.9(1.42)(2.0)(0.200) = 0.51$

Use $C_{pi} = 0.51$

Alternative Design Method (Section 12.10.3)



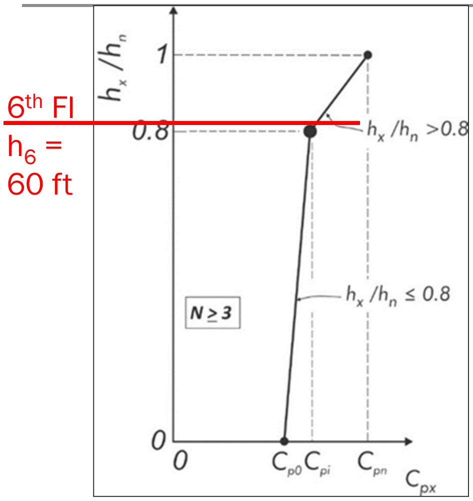
- Diaphragm Design Acceleration Coefficient at the Structure Height, h_n

$$C_{pn} = \sqrt{(\Gamma_{m1}\Omega_0 C_s)^2 + (\Gamma_{m2} C_{s2})^2}$$

$$C_{pn} = \sqrt{(1.42 \times 2 \times 0.200)^2 + (0.625 \times 1.2)^2}$$

= 0.94 (Eq. 12.10−7)

Alternative Design Method (Section 12.10.3)



- C_{p0} = 0.48
- C_{pi} = 0.51
- C_{pn} = 0.94
- $0.8h_n$ = 0.8(72 ft) = 57.6 ft

Alternative Design Method (Section 12.10.3)

Diaphragm Design Acceleration Coefficient at 6th Floor

h_6 = 5 (12) = 60 ft

C_{p6} = 0.51 + (0.94-0.51) (60-57.6)/12 = 0.60 (linear interpolation)

$$F_{p6} = \frac{C_{p6}}{R_s} w_{p6}$$

$$= \frac{0.60}{2.0} 1,570 = 471 \text{ kips}$$

But not less than:

$F_{p6} = 0.2 S_{DS} I_e w_{px}$ (ASCE/SEI 7-22 Eq. 12.10-5)

= 0.2(1.2)(1.0)(1,570) = 377 kips (floor)

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Alternative Design Method (Section 12.10.3)

Table 7.5-4: Summary of Section 12.10.3 Alternative Diaphragm Design Forces, F_{px}, (kips)

Level	C_{px}	F_{px} Eq. 12.10-4 Force (kips)	F_{px} Minimum (kips)	F_{px} Design (kips)
Roof	0.94	778	199	778
6	0.60	471	377	471
5	0.51	400	377	400
4	0.50	392	377	392
3	0.49	385	377	385
2	0.49	385	377	385

1.0 kip = 4.45 kN

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Alternative Design Method (Section 12.10.3)

Step 5 – Diaphragm Transfer Forces

- Diaphragm transfer forces, as defined in ASCE/SEI 7-22 Section 11.2, occur where vertical elements of the SFRS are offset or discontinued at lower levels; they also occur due to changes in the stiffness of the SFRS vertical elements between levels. The occurrence of diaphragm transfer forces is determined by examining the distribution of forces from the analysis model.
- For simplicity, the building in this example building is assumed to not have diaphragm transfer forces.

Alternative Design Method (Section 12.10.3)

Step 6 – Design for Shear and Flexure

- Diaphragms at each level are designed for shear and flexure using the tabulated F_{px} design forces. Should diaphragm transfer forces be applicable these would also be included and be amplified where required (ASCE/SEI 7-22 Section 12.10.3.3).
- Where a computer analysis model is used, this can involve taking the shear and flexure forces at the F_x level from the model and amplifying them to the F_{px} level.
- For diaphragms idealized as rigid or semi-rigid, inherent torsion, accidental torsion and transfer forces are addressed in the building model such that the extracted shear and flexure forces include these effects.

Alternative Design Method (Section 12.10.3)

Step 7 - Collector Seismic Design Forces

Collectors in the example building are, per ASCE/SEI 7-22 Section 12.10.3.4, required to be designed for amplified seismic forces. In lieu of the overstrength requirements of ASCE/SEI 7-22 Section 12.10.2.1, the collectors are required to be amplified by a factor of 1.5. Just like the seismic load effect with overstrength provisions of ASCE/SEI 7-22 Section 12.4.3, the amplified forces are required to be used in the appropriate load combinations from ASCE/SEI 7-22 Chapter 2. The following demonstrates the calculation of the collector seismic design forces due to horizontal seismic loads. This will need to the combined with applicable gravity loads and vertical seismic forces.

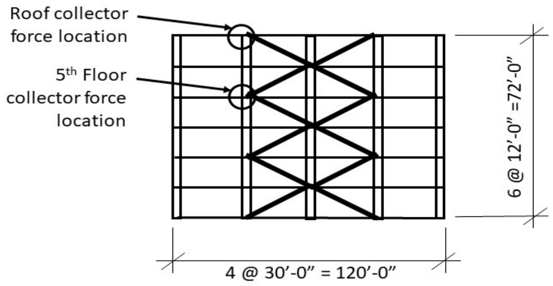
Alternative Design Method (Section 12.10.3)

Diaphragm Transverse Force Reactions and Units Shears

Roof Diaphragm V = 778 kips /2 = 389 kips
v = 389 kips / 120 ft
= 3.24 klf

5th Flr diaphragm V = 400 (1.1*) kips / 2
= 220 kips
v = 220 kips / 120 ft
= 1.83 klf

* Extracted from analysis, value will vary



Elevation AA

Alternative Design Method (Section 12.10.3)

- Collector Force at Location shown in Figure, amplified by 1.5 (in lieu of Ω_0)
- Roof Diaphragm T/C = 3.24 klf (30 ft) (1.5) = 146 kips
- 5th Floor Diaphragm T/C = 1.83 klf (30 ft) (1.5) = 82 kips

Alternative Design Method (Section 12.10.3)

Step 8 – Deflection and Drift Requirements

For ELF design, this step incorporates the revised displacement and drift determination provisions of ASCE/SEI 7-22 Section 12.8.6 and the drift and deformation provisions of Section 12.12.

The structural separation provisions of Section 12.12.2, structural separation requirements of Section 12.12.3, and deformation compatibility provisions of 12.12.4 each require that diaphragm deflection be considered in addition to the deflection of the vertical elements.

Example Multi-Story Steel Building with Steel Deck Diaphragms

Comparison of Methods

Comparison of Design Methods

Table 7.5-5: Comparison of Traditional and Alternative F_{px} Diaphragm Design Forces (kips)

Level	F_{px} Traditional ASCE/SEI 7-22 Section 12.10.1 and 12.10.2 (kips)	F_{px} Alternative ASCE/SEI 7-22 Section 12.10.3 (kips)
Roof	302	778 (R_s =1.0)
6	510	471
5	460	400
4	411	392
3	377	385
2	377	385

1.0 kip = 4.45 kN

Comparison of Design Methods

For this structure and the diaphragm systems used, the alternative method force is higher than the traditional method at some diaphragm levels (particularly at the roof), and lower at others. The much higher diaphragm design force at the roof comes from the combination of using the alternative method, and the very low values of R_s = 1.0 for the welded bare steel deck diaphragm that is recognized in ASCE/SEI 7-22 to have low ductility. If the roof diaphragm were instead changed to conform to the special seismic detailing requirements, the roof diaphragm design forces would essentially match the traditional method forces.

Comparison of Design Methods

Table 7.5-6: Comparison of Traditional and Alternative Diaphragm Collector Forces

Level	Traditional ASCE/SEI 7-22 Section 12.10.1 and 12.10.2 (kips)	Alternative ASCE/SEI 7-22 Section 12.10.3 (kips)
Roof	76	146 (R_s = 1.0)
5	127	82

1.0 kip = 4.45 kN, 1.0 ft = 0.3048 m, 1.0 ft-kip = 1.36 kN-m

Part 1 Closing Comments

Questions

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