Chapter 8 Nonstructural Components: Fundamentals and Design Examples

2020 *NEHRP Provisions* Training Materials

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Learning Objectives

- Understand the parameters influencing nonstructural response
- Understand key changes coming in ASCE/SEI 7-22, including
  - The new seismic design force equation
  - How equipment support structures and platforms are handled
  - How distribution system supports are handled
- Understand how to use the 2020 *NEHRP Provision Design Examples* as a resource for nonstructural component design

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Outline of Presentation

Fundamentals

- Overview and code development process
- Parameters influencing nonstructural response
- Seismic design force equation
- Equipment support structures and platforms and distribution system supports
- Accommodation of seismic relative displacements
- Code change summary

Design Examples

- Architectural concrete wall panel
- Seismic analysis of egress stairs
- HVAC fan unit support
- Piping system seismic design
- Elevated vessel seismic design

Note: Images without references are taken from FEMA P-2192-V1. Full references for partial citations are given in FEMA P-2192-V1.

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Fundamentals

Nonstructural Components

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Nonstructural Components

- Defined as "a part of an architectural, mechanical, or electrical system within or without a building or nonbuilding structure" (ASCE/SEI 7-22 Section 11.2)
- These items make up the majority of the replacement value of most buildings.
- Design based on two fundamentally different demands:
  - Resistance to inertial forces (seismic forces)
  - Accommodation of imposed displacements

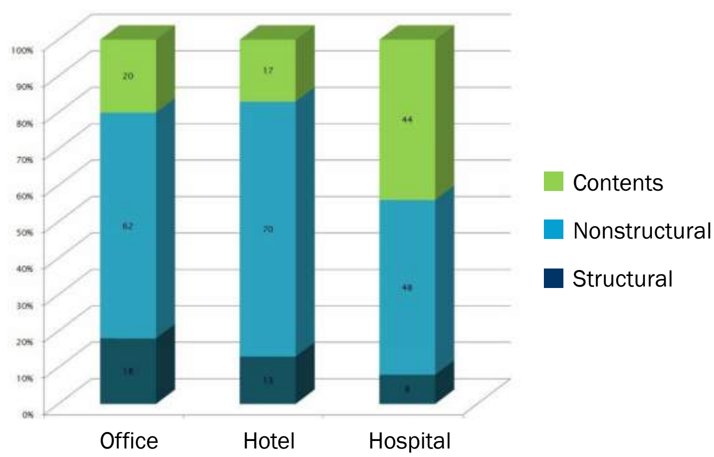
Suspended Acoustic Tile Ceilings Restrained by Compression Struts and Diagonal Splayed Wires

(from FEMA E-74, 2012, *Reducing the Risks of Nonstructural Earthquake Damage—A Practical Guide)*

Relative Costs

The largest capital investment in most commercial buildings is in the nonstructural systems and contents.

Image from FEMA E-74 (2012) and Whittaker, A.S. and Soong, T.T. (2003). "An overview of nonstructural component research at three U.S. earthquake engineering research centers," in *Proceedings of Seminar on Seismic Design, Performance, and Retrofit of Nonstructural Components in Critical Facilities*, Applied Technology Council, ATC-29-2, pp. 271-280, Redwood City, California.



Typical investments in building construction

Anticipated Behavior of Noncritical Nonstructural Components From ASCE/SEI 7-22 Sections C13.1 and C13.1.3

Minor Earthquake

- Minimal damage, not likely to affect functionality

Moderate Earthquake

- Some damage that might affect functionality

Design Earthquake

- Major damage but significant falling hazards are avoided; likely loss of functionality

MCE_R Earthquake

- No implicit performance goals

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ASCE/SEI 7-22 Chapter 13: Seismic Design Requirements for Nonstructural Components

Section 13.1

- Information on applicability of nonstructural design provisions

Section 13.2

- Importance of the component or system
- Adequacy of component for seismic forces and certification requirements

Section 13.3

- Acceleration and displacement demands for nonstructural components

Section 13.4

- Design considerations for attachments of nonstructural components to the structure

Section 13.5

- Design considerations for architectural components

Section 13.6

- Design considerations for mechanical and electrical components

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Code Development Process for Recent Revisions to Nonstructural Provisions

- General Research (through 2018)
- ATC-120 Phase 2 (2016-2018) / NIST GCR 18-914-43 (2018)
  - Synthesize past research
  - Project research and analyses
  - Recommended equation
- BSSC PUC (2018-2020)
  - Issue Team 5 develops code proposal
  - Main PUC reviews, makes recommendations, ballots proposal
  - BSSC member orgs. ballot proposal
  - 2020 *NEHRP Provisions* published
- ASCE 7 Code Committee (2020-2021)
  - Nonstructural Issue Team refines proposal
  - ASCE 7 Seismic Subcommittee ballots proposal
  - Main committee ballots proposal
  - Public comment
  - Final approval for ASCE/SEI 7-22
  - ASCE/SEI 7-22 published

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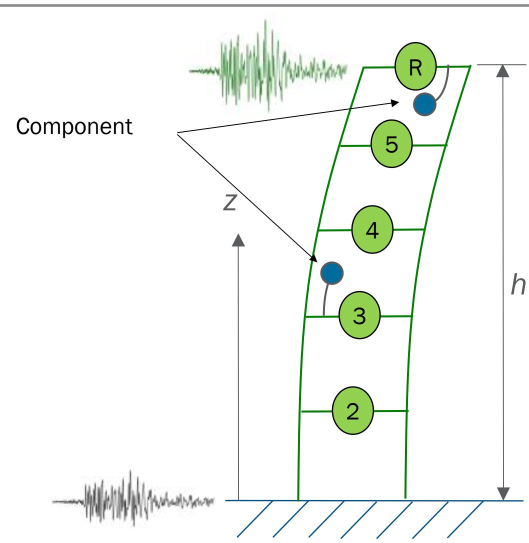
Key Terminology

- PCA: Peak Component Acceleration
- PFA: Peak Floor Acceleration
- PGA: Peak Ground Acceleration



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Parameters Influencing Nonstructural Response

- Ground shaking intensity, PGA
- Building
  - Seismic force-resisting system
  - Building modal period, $T_{n,bldg}$
  - Building ductility, μ_{bldg}
  - Building damping, β_{bldg}
  - Building configuration (such as plan and vertical irregularities)
  - Floor diaphragm rigidity
- Height of component within the building, z/h
- Component
  - Component period, T_{comp}
  - Component and/or anchorage ductility, μ_{comp}
  - Component damping, β_{comp}
  - Component reserve strength margin, $R_{po,comp}$

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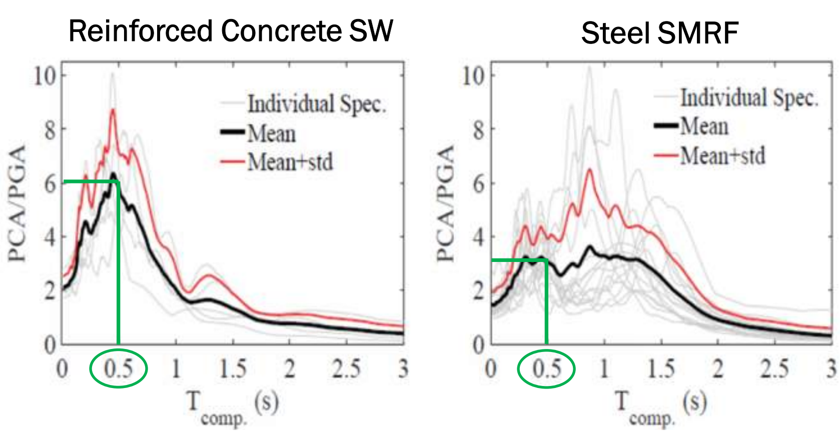
Seismic Force-Resisting System

T_{comp} = 0.5 sec



Effect of building stiffness on PCA/PGA for instrumental recordings
(from NIST GCR 18-917-43, 2018 and Lizundia paper in 2019 SEAOC Convention Proceedings)

Key Takeaway

- Same component responds very differently in different seismic force-resisting systems

Figure Assumptions

- Elastic component assumed with β_{comp}=5%
- Dataset includes 19 recordings with PGA>0.15g

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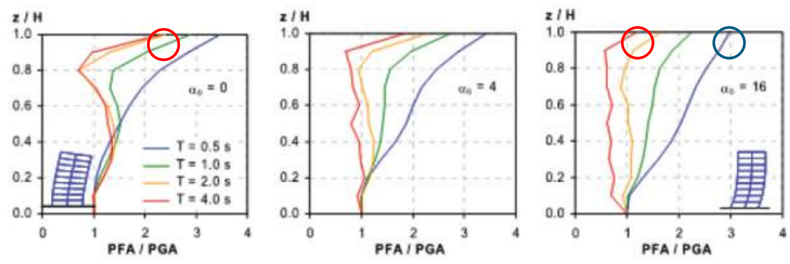
Building Modal Periods, $T_{n,bldg}$



Effect of period of vibration and lateral system stiffness on PFA/PGA

Key Takeaway

- Longer period means less amplification
- Cantilever systems have more "whipping" action

α_0= Lateral stiffness ratio, defined as $\alpha_0 = H/(GA/EI)^{0.5}$

H = height,

GA = shear rigidity of a shear beam

EI = the flexural stiffness

α_0 = 0 represents a pure flexural model

α_0 approaching infinity represents a pure shear beam

(from Miranda and Taghavi, 2009)

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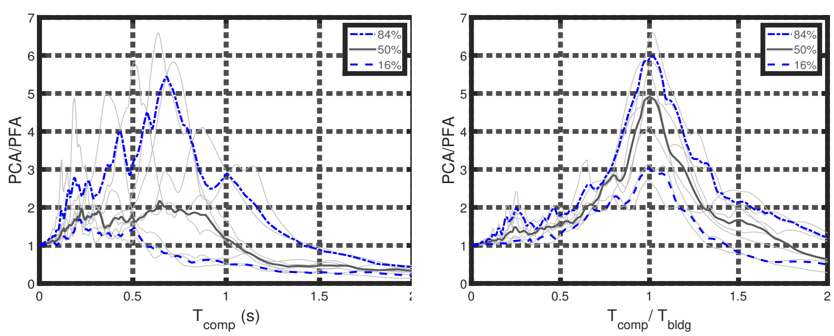
Component Period, T_{comp}, and Building Period Resonance



Relationship between PCA/PFA comparing spectra without normalization (left) and with normalization (right) by T_{bldg} *(from Kazantzi et al., 2019)*

Key Takeaway

- Normalized x-axis is helpful to understand influence of building in component response

Figure Assumptions

- Elastic component with β_{comp}=5%
- Dataset includes eight recordings with PCA>0.9g

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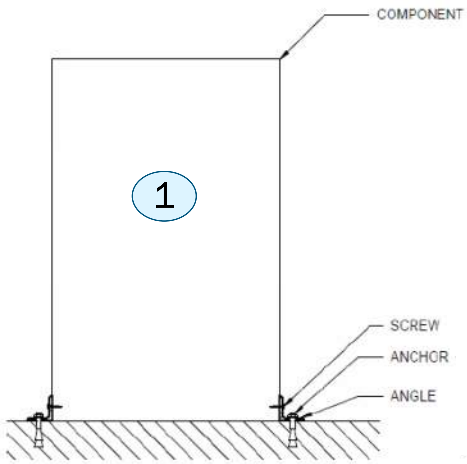
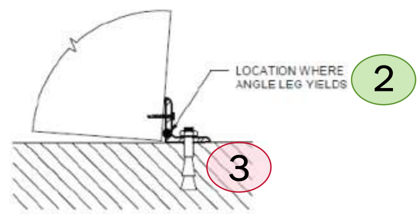
Sources of Component and/or Anchorage Ductility



1. Component
2. Connection of component to anchor
3. Anchor



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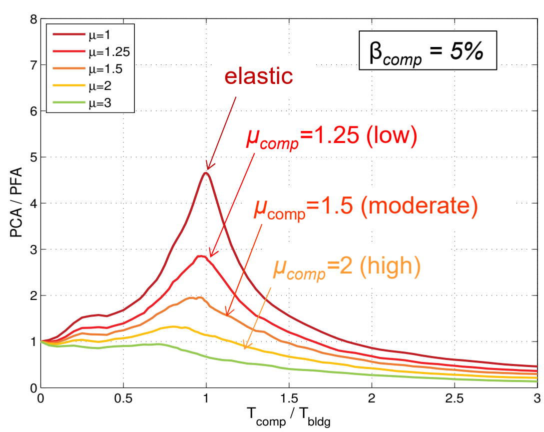
Component/Anchorage Ductility, μ_{comp}



Mean response of PCA/PFA versus T_{comp}/T_{bldg} for different levels of component ductility *(from NIST, 2018 and Lizundia, 2019)*

Key Takeaway

- Ductility substantially reduces component response, particularly at resonance

Figure Assumptions

- Elastic component assumed with β_{comp}=5%
- Dataset includes 86 recordings with PCA>0.9g

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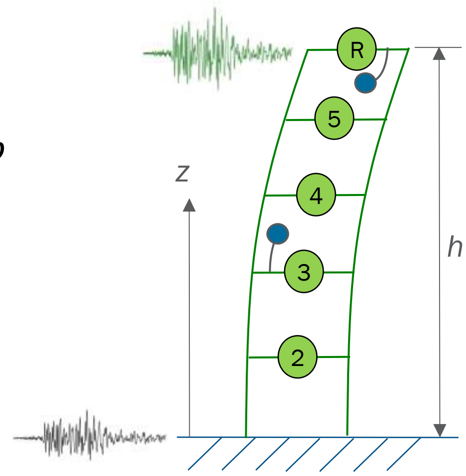
ATC-120 Proposed Seismic Design Force Equation

$$\frac{F_p}{W_p} = \mathrm{PGA} \times \left[\frac{\left(\frac{\mathrm{PFA}}{\mathrm{PGA}}\right)}{R_{\mu bldg}}\right] \times \left[\frac{\left(\frac{\mathrm{PCA}}{\mathrm{PFA}}\right)}{R_{po,bldg}}\right] \times \mathrm{I}_p$$

Reduction factor for building ductility

Reduction factor for component reserve strength



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Evolution of Seismic Design Force Equation

ASCE 7-16

$$\frac{F_p}{W_p} = (0.4S_{DS}) \times \left[1 + 2\left(\frac{z}{h}\right)\right] \times \left[\frac{a_p}{R_p}\right] \times I_p$$

NIST GCR 18-917-43 (ATC-120)

$$\frac{F_p}{W_p} = \mathrm{PGA} \times \left[\frac{\left(\frac{\mathrm{PFA}}{\mathrm{PGA}}\right)}{R_{\mu bldg}}\right] \times \left[\frac{\left(\frac{\mathrm{PCA}}{\mathrm{PFA}}\right)}{R_{po,bldg}}\right] \times I_p$$

2020 *NEHRP Provisions* and ASCE 7-22

$$\frac{F_p}{W_p} = (0.4S_{DS}) \times \left[\frac{H_f}{R_\mu}\right] \times \left[\frac{C_{AR}}{R_{po}}\right] \times I_p$$

Ground response

PFA/PGA

Resonance and component ductility

Component strength reserve margin

Building ductility

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PFA/PGA (H_f) Amplification Factor

$$H_f = 1 + a_1\left(\frac{z}{h}\right) + a_2\left(\frac{z}{h}\right)^{10}$$

or:

$$H_f = 1 + 2.5\left(\frac{z}{h}\right)$$

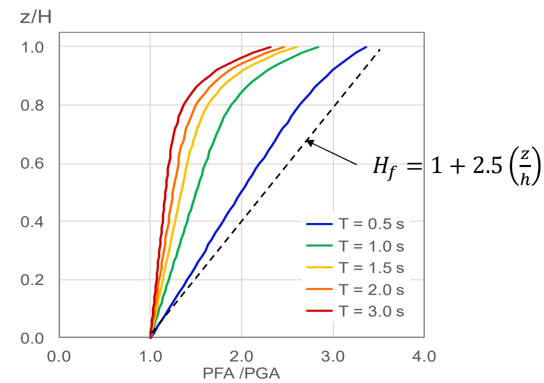
where:

$$a_1 = \frac{1}{T_a} \leq 2.5$$

$$a_2 = [1 - (0.4/T_a)^2] \geq 0$$

$$T_a = C_t h_n^x$$

$$\frac{F_p}{W_p} = (0.4 S_{DS}) \times \left[\frac{H_f}{R_\mu}\right] \times \left[\frac{C_{AR}}{R_{po}}\right] \times I_p$$



Building Ductility, R_μ

$$R_\mu = (1.1\,R/(\,I_e\,\Omega_0))^{1/2} \geq 1.3$$

$$\frac{F_p}{W_p} = (0.4 S_{DS}) \times \left[\frac{H_f}{R_\mu}\right] \times \left[\frac{C_{AR}}{R_{po}}\right] \times I_p$$

where:

- R = Response modification factor for the building or nonbuilding structure
- I_e = Importance Factor for the building or nonbuilding structure
- Ω_0 = Overstrength factor for the building or nonbuilding structure

For components at or below grade, R_μ shall be taken as 1.0.

PCA/PFA (C_{AR})

		Component Ductility		
Location of Component	Resonance	Category	Assumed Ductility	$\left(\frac{\text{PCA}}{\text{PFA}}\right)$
Ground	More Likely	Elastic	μ_{comp}=1	2.5
		Low	μ_{comp}=1.25	2.0
		Moderate	μ_{comp}=1.5	1.8
		High	μ_{comp}≥2	1.4
	Less Likely	Any	-	1.0
Roof or Elevated Floor	More Likely	Elastic	μ_{comp}=1	4.0
		Low	μ_{comp}=1.25	2.8
		Moderate	μ_{comp}=1.5	2.2
		High	μ_{comp}≥2	1.4
	Less Likely	Any	-	1.0

$$\frac{F_p}{W_p} = (0.4S_{DS}) \times \left[\frac{H_f}{R_\mu}\right] \times \left[\frac{C_{AR}}{R_{po}}\right] \times I_p$$

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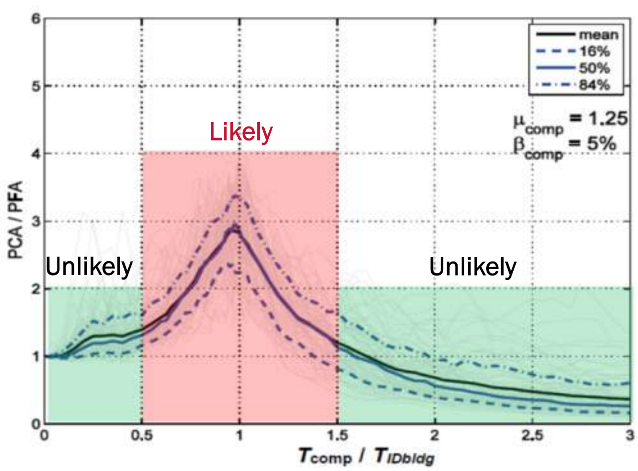
Unlikely vs. Likely to be in Resonance



Unlikely to be in resonance:

- T_{comp}/T_{bldg} < 0.5
- T_{comp}/T_{bldg} > 1.5
- $T_{comp} \leq 0.06$

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Component Resonance Ductility Factor, C_{AR}, and Component Strength, R_{po}

- Architectural components shall be assigned a factor per ASCE/SEI 7-22 Table 13.5-1
- Mechanical and electrical equipment shall be assigned a factor per ASCE/SEI 7-22 Table 13.6-1

$$\frac{F_p}{W_p} = (0.4S_{DS}) \times \left[\frac{H_f}{R_\mu}\right] \times \boxed{\left[\frac{C_{AR}}{R_{po}}\right]} \times I_p$$

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Alternative Procedure for Nonlinear Response History Analysis

$$\frac{F_p}{W_p} = \boxed{0.4S_{DS}} \times \boxed{a_i} \times \boxed{\left[\frac{C_{AR}}{R_{po}}\right]} \times I_p$$

where:

a_i = Maximum acceleration at Level *i* obtained from nonlinear response history analysis at the design earthquake ground motion.

- a_i replaces the ratio $\frac{H_f}{R_\mu}$ in main seismic design force equation
- The nonlinear analysis can account for the following parameters:
  - H_f, variation of acceleration up the height of the structure specific to its dynamic properties
  - R_μ, reduction of PFA due to the structure's ductility

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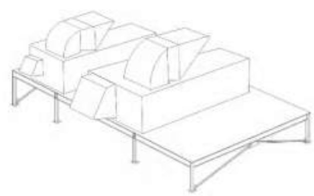
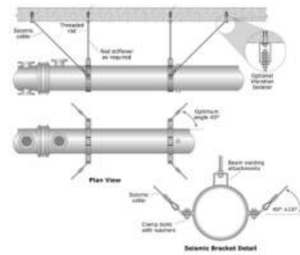
Equipment Support Structures and Platforms and Distribution System Supports

Three different types of supports:

Nonstructural component with integral equipment supports



Equipment support platform supporting two mechanical components



Distribution system support for piping

Images from FEMA P-2082-1 (2020) and FEMA E-74 (2012)

Accommodation of Seismic Relative Displacements

$$D_{pI} = D_p I_e$$

- Displacement **within** Structure A between Level *x* and Level *y*

$$D_p = \delta_{xA} - \delta_{yA}$$

but not greater than:

$$D_p = \frac{(h_x - h_y)\Delta_{aA}}{h_{sx}}$$

- Displacement **between** Structures A and B between Level *x* and Level *y*

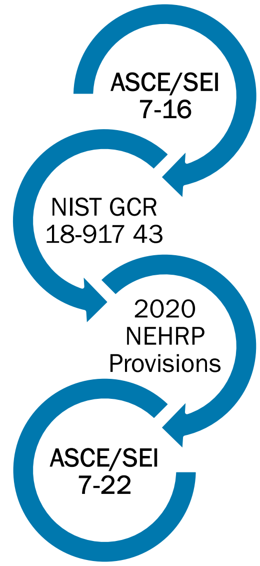
$$D_p = |\delta_{xA}| + |\delta_{yB}|$$

but not greater than:

$$D_p = \frac{h_x \Delta_{aA}}{h_{sx}} + \frac{h_y \Delta_{aB}}{h_{sx}}$$

Development of Nonstructural Seismic Design Force Equations

- The revisions for the nonstructural seismic design force equations in ASCE/SEI 7-22 are based on the following publications:
  - NIST GCR 18-917-43: *Recommendations for Improved Seismic Performance of Nonstructural Components (2018)*, produced by the Applied Technology Council ATC-120 project
  - 2020 *NEHRP Recommended Seismic Provisions for New Buildings and Other Structures*, used to develop code proposals for ASCE/SEI 7-22



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Proposed Equations in NIST GCR 18-917-43

- Key features in the proposed equations:
  - Refinement to relate PFA to PGA at different heights in the building and incorporate the building period, *T*
  - Inclusion of building ductility. Increased building ductility generally reduces nonstructural component response.
  - Refinement of relationship between PCA and PFA to account for resonance due to ratio of component period-to-building period and component ductility

ATC-120 Phase 2 (2016-2018/ NIST GCR 18-917-43 (2018)

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Proposed Equations in NIST GCR 18-917-43

- Key features in the proposed equations (continued):
  - Differentiation between ground-supported and superstructure-supported components for amplification factors
  - Inclusion of components and attachments inherent overstrength, R_{po}
  - Revision to architectural component categories in ASCE/SEI 7-16 Table 13.5
  - Distinction addressing different parameters for the component and the equipment support structure

ATC-120 Phase 2 (2016-2018/ NIST GCR 18-917-43 (2018)

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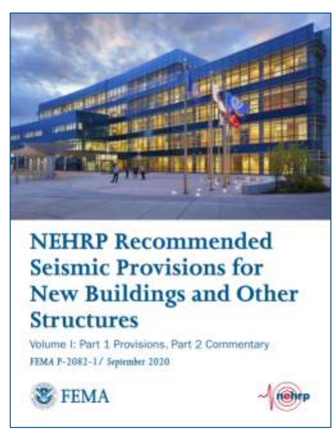
Revisions in the 2020 *NEHRP Provisions*

- The NIST GCR 18-917-43 recommendations were used to develop code proposals for the 2020 *NEHRP Provisions*, which include the following key issues:
  - Terminology revision: PGA → $0.4S_{DS}$, PFA/PGA → H_f, PCA/PFA → C_{AR}, $R_{\mu bldg}$ → R_μ, R_{pocomp} → R_{po}
  - R_μ clarification, R_μ=1.0 for ground supported components
  - Assignment of C_{AR}, R_{po}, and Ω_{op} values for different components based on ductility and likelihood of resonance
  - Separation of elevators and escalators in Table 13.6-1 into two different categories



2020 *NEHRP Provisions*

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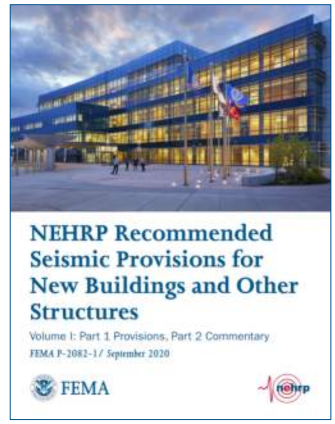
Revisions in the 2020 *NEHRP Provisions*

- The NIST GCR 18-917-43 recommendations were used to develop code proposals for the 2020 *NEHRP Provisions*, which include the following key issues:
  - R_{po} refinement for reasonable value for most components
  - Maximum (cap) value consensus of $1.6S_{DS}I_pW_p$ to be compatible with analytical results
  - Overstrength factor in concrete and masonry, Ω_{op} compatible with the F_p equation
  - Addition of detailed provisions for different types of supports
  - Clarification and improved requirements for seismic design of penthouses and rooftop structures



2020 *NEHRP Provisions*

Revisions for ASCE/SEI 7-22

- The 2020 *NEHRP Provisions* were used to develop code proposals for ASCE/SEI 7-22, which include the following key issues:
  - Seismic Importance Factor, I_e, added to the denominator of the R_μ equation
  - Revision to specify direction of loading using F_p
  - Increase of Ω_{op} values for selected architectural components in Table 13.5-1 and mechanical and electrical components in Table 13.6-1
  - Increase of R_{op} values for selected piping systems and duct systems for mechanical and electrical components in Table 13.6-1

Significant Changes from ASCE/SEI 7-16 to ASCE/SEI 7-22

- Definition of equipment supports (Section 11.2)
- Detailed scope of design criteria for nonstructural components (Section 13.1)
- Explicit load combinations for nonstructural components (Section 13.2.2)
- Required analysis for condition where the nonstructural component weight is equal to or greater than 20% the combined effective seismic weight, *W* (Section 13.2.9)
- Updated horizontal seismic design forces, F_p (Section 13.3.1)
  - Equation and coefficients are more rigorously based in instrumental records and analytical findings and better account for key parameters that affect response.
- Seismic design force provision using nonlinear response history analysis is updated; other dynamic analysis methods are removed (Section 13.3.1.5).

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Significant Changes from ASCE/SEI 7-16 to ASCE/SEI 7-22 (cont.)

- Ω_{0p} is required to increase the load effects for anchors in concrete or masonry, instead of Ω_0 (Section 13.4.2).
- Architectural component list is expanded, and items account for updated coefficient for seismic design: C_{AR}, R_{po}, and Ω_{0p} (Table 13.5-1).
  Example: Partitions split into short light frame, tall light frame, reinforced masonry and other
- Penthouse and rooftop structure requirements are added (Section 13.5.11).
- Mechanical and electrical component list is expanded, and items account for updated coefficient for seismic design: C_{AR}, R_{po}, and Ω_{0p} (Table 13.6-1).
- Equipment support structures and platforms are required to be designed (Section 13.6.4.6).
- Distribution system supports are required to be designed (Section 13.6.4.7).

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Minor Changes from ASCE/SEI 7-16 to ASCE/SEI 7-22

- Seismic Design Category applicability is extended (Section 13.1.2).
- Component Importance Factor, I_p (Section 13.1.3)
- Nonstructural components exempt from seismic requirements are summarized in a table (Section 13.1.4).
- Most of general design requirements remain the same, with the exceptions noted previously (Section 13.2).
- Specific requirements for architectural components are mostly unchanged (Section 13.5).
- Except for the support conditions, specific requirements for mechanical and electrical components are mostly unchanged (Section 13.6).

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Unchanged in ASCE/SEI 7-22 (same as ASCE/SEI 7-16)

- Horizontal seismic forces maximum and minimum values remain the same (Section 13.3.1).

$$\frac{F_p}{W_p} \leq 1.6 S_{DS} I_p \qquad \text{(Equation 13.3-2)}$$

$$\frac{F_p}{W_p} \geq 0.3 S_{DS} I_p \qquad \text{(Equation 13.3-3)}$$

- Seismic relative displacements equations are unchanged (Section 13.3.2).
- Component fundamental period is determined with the same equation (Section 13.3.3).

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Questions?

Design Examples

Nonstructural Components

Design Examples for Architectural Components

- Architectural concrete wall panel
  - Providing gravity support and accommodating story drift in cladding
  - Spandrel panel
  - Column cover
  - Prescribed seismic displacements
- Seismic analysis of egress stairs
  - Prescribed seismic forces
  - Prescribed seismic displacements
- HVAC fan unit support
  - Case 1: Direct attachment to structure
  - Case 2: Support on vibration isolation springs
- Piping system seismic design
  - Piping system design
  - Pipe supports and bracing
  - Prescribed seismic displacements
- Elevated vessel seismic design
  - Vessel support and attachments
  - Supporting frame

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Architectural Concrete Wall Panel

- Providing gravity support and accommodating story drift in cladding
- Spandrel panel
- Column cover
- Prescribed seismic displacements

Public domain image from piqsels.com

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Architectural Concrete Wall Panel Description

Example Summary

- **Nonstructural component:** Architectural – exterior nonstructural wall elements and connections
- **Building seismic force-resisting system:** Steel special moment frames
- **Equipment support:** Not applicable
- **Occupancy:** Office
- **Risk Category:** II
- **Component Importance Factor:** $I_p = 1.0$
- **Number of stories:** 5
- $S_{DS} = 1.487$

- Architectural components are a 4.5-inch-thick NWC spandrel panel and column cover
- Spandrel panel supports glass windows weighing 10 psf
- The girders at Level 3 support the spandrel panel under consideration.
- The column cover under consideration is between Level 3 and Level 4.

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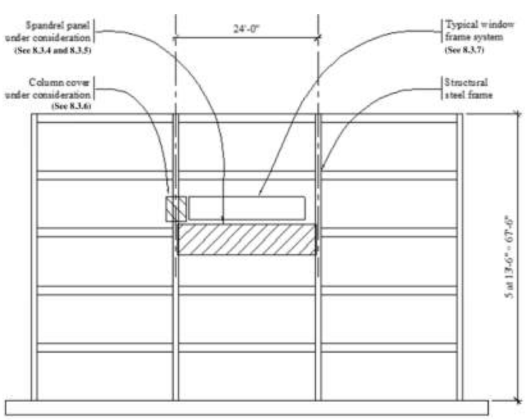
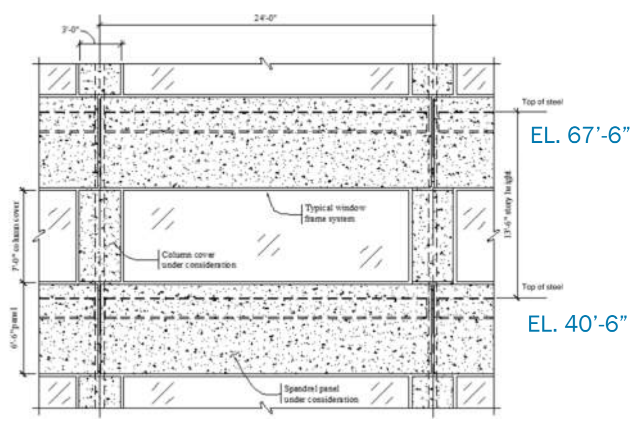
Architectural Concrete Wall Panel Description



Five-story building showing panels location



Detailed building elevation

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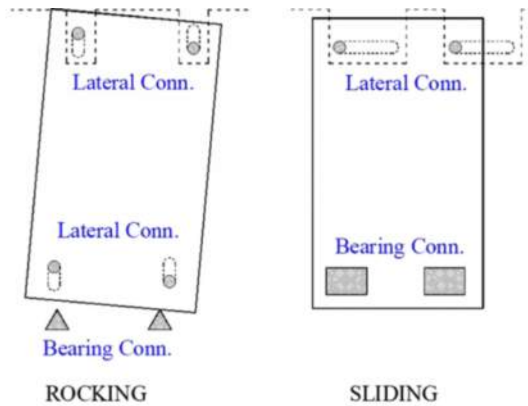
Providing Gravity Support and Accommodating Story Drift in Cladding

- Understanding the cladding system components is the first step for the concrete precast panel seismic design.
- Two crucial items should be determined:
  - Gravity support approach for the precast panel components
  - Mechanism to accommodate story drift
- Approaches to accommodate interstory drift
  - Rocking
  - Sliding



Rocking and sliding mechanisms in panels

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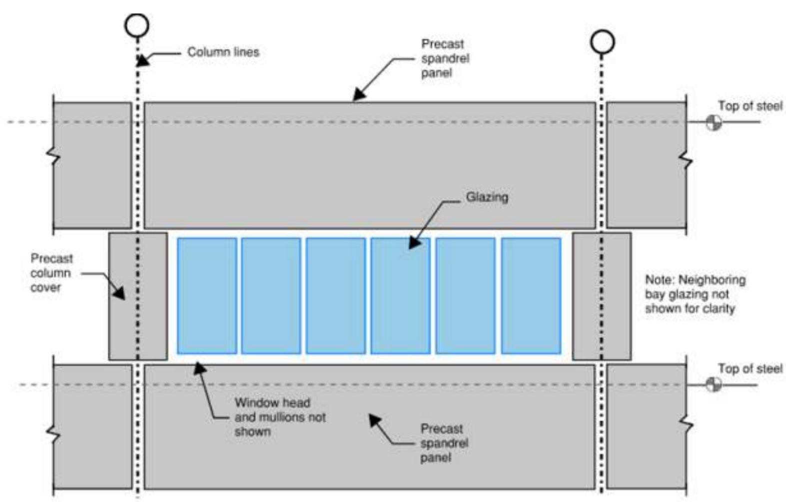
Rocking Cladding Connection System



Initial position

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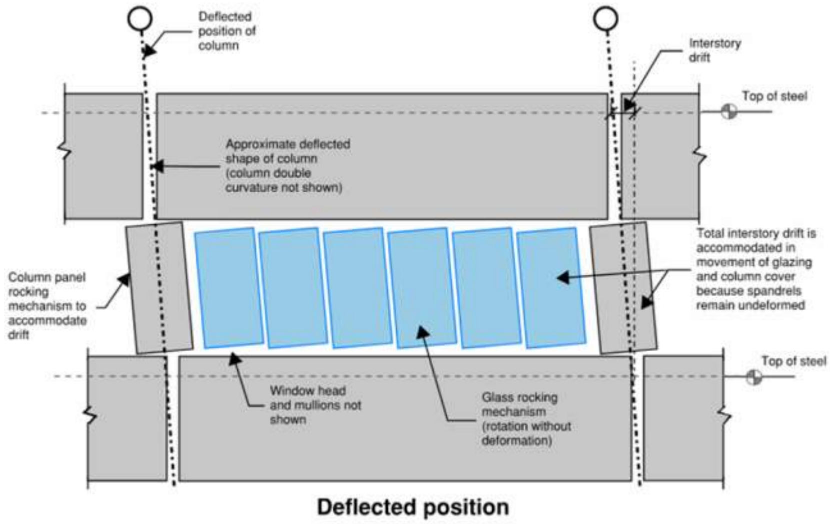
Rocking Cladding Connection System



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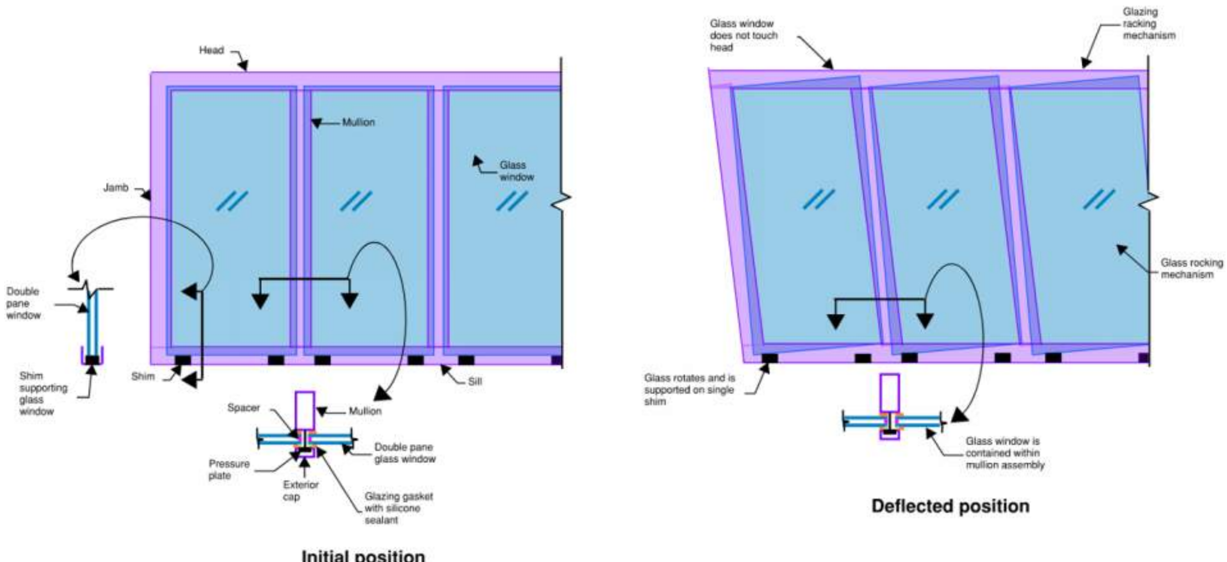
Window Framing System Racking Mechanism



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ASCE/SEI 7-22 Parameters and Coefficients

Coefficients for Architectural Components (Table 13.5-1)

- Exterior nonstructural wall elements and connections – wall element, and body of wall panel connections:
  - $C_{AR} = 1.0$
  - $R_{po} = 1.5$
  - $\Omega_{0p} = 2.0$
- Exterior nonstructural wall elements and connections – fasteners of the connecting system:
  - $C_{AR} = 2.8$
  - $R_{po} = 1.5$
  - $\Omega_{0p} = 1.0$

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ASCE/SEI 7-22 Parameters and Coefficients

- Design coefficients and factors for seismic force-resisting system (Table 12.2-1)
  Steel SMRF: $R = 8.0$ and $\Omega_0 = 3.0$
- Short period design spectral acceleration, $S_{DS} = 1.487$
- Seismic Importance Factor, $I_e = 1.0$
- Component Importance Factor, $I_p = 1.0$
- Redundancy factor, $\rho = 1.0$
- Height of attachment at Level 3, $z = 40.5 \text{ ft}$
- Average roof height, $h = 67.5 \text{ ft}$
- Story height, $h_{sx} = 13.5 \text{ ft}$

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ASCE/SEI 7-22 Parameters and Coefficients

- Spandrel panel weight

  $W_p = (150 \text{ lb/ft}^3)(24 \text{ ft long})(6.5 \text{ ft high})(4.5 \text{ in. thick}/12 \text{ ft/in.}) = 8{,}775 \text{ lb}$
- Glass weight,

  $W_p = (10 \text{ lb/ft}^2)(21 \text{ ft long})(7 \text{ ft high}) = 1{,}470 \text{ lb}$
- Column cover weight,

  $W_p = (150 \text{ lb/ft}^3)(3 \text{ ft wide})(7 \text{ ft high})(4.5 \text{ in. thick}/12 \text{ ft/in.}) = 1{,}181 \text{ lb}$
- Approximate fundamental period of the supporting structure, T_a (Section 12.8.2.1)

  Steel SMRF: $T_a = C_t {h_n}^x = (0.028)(67.5 \text{ ft})^{0.8} = 0.81 \text{ s}$

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ASCE/SEI 7-22 Parameters and Coefficients

- Force amplification factor as a function of height in the structure, H_f

  $a_1 = \frac{1}{T_a} = \frac{1}{0.81 \text{ s}} = 1.23 \leq 2.5$

  $a_2 = [1 - (0.4/T_a)^2] = [1 - (0.4/0.81 \text{ s})^2] = 0.76 \geq 0$

  $H_f = 1 + a_1 \left(\frac{z}{h}\right) + a_2 \left(\frac{z}{h}\right)^{10} = 1 + 1.23 \left(\frac{40.5 \text{ ft}}{67.5 \text{ ft}}\right) + 0.76 \left(\frac{40.5 \text{ ft}}{67.5 \text{ ft}}\right)^{10} = 1.74$

  Compare H_f value using alternative equation that does not require T_a:

  $H_f = 1 + 2.5 \left(\frac{z}{h}\right) = 1 + 2.5 \left(\frac{40.5 \text{ ft}}{67.5 \text{ ft}}\right) = 2.50$ (44% increase)
- Structure ductility reduction factor, R_μ

  $R_\mu = (1.1\, R/(I_e \Omega_0))^{1/2} = (1.1(8/((1)(3)))^{1/2} = 1.71 \geq 1.3$

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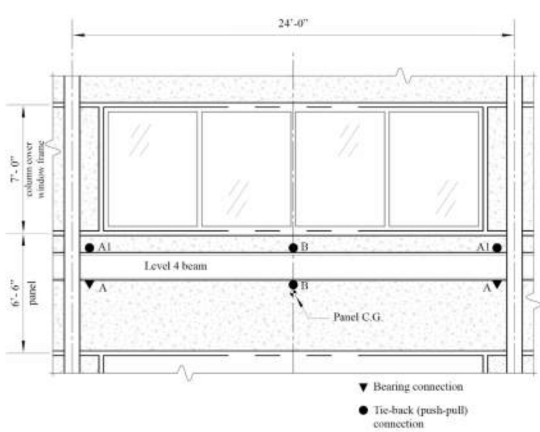
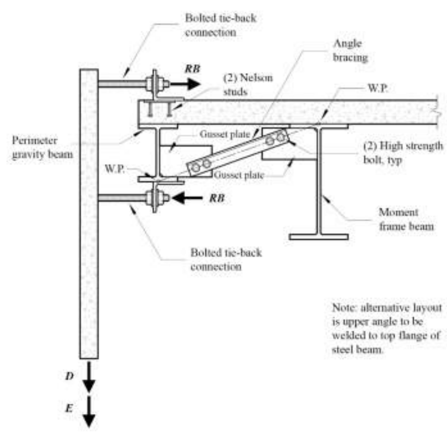
Applicable Requirements

- Component failure shall not cause failure of an essential architectural, mechanical, or electrical component (Section 13.2.4).
- Seismic attachments shall be bolted, welded, or otherwise positively fastened without considering the frictional resistance produced by the effects of gravity (Section 13.4).
- F_p shall be applied at the component's center of gravity and distributed relative to the component's mass distribution (Section 13.3.1).
- Effects of seismic relative displacements shall be considered in combination with displacements caused by other loads as appropriate (Section 13.3.2).
- Exterior nonstructural wall panels or elements that are attached to or enclose the structure shall be designed to accommodate the seismic relative displacements, and movements caused by temperature changes (Section 13.5.3).

Spandrel Panel Layout



Spandrel panel layout connection from interior



Spandrel panel section at midspan

Prescribed Seismic Forces: Wall Element and Body of Wall Panel Connections

- Spandrel panel and glass weight, $W_p = D = 8{,}775\text{ lb} + 1{,}470\text{ lb} = 10{,}245\text{ lb}$
- Seismic design force, F_p

$$F_p = 0.4S_{DS}I_pW_p\left[\frac{H_f}{R_\mu}\right]\left[\frac{C_{AR}}{R_{po}}\right] = 0.4(1.487)(1.0)(W_p)\left[\frac{1.74}{1.71}\right]\left[\frac{1.0}{1.5}\right] = 0.403W_p$$

$$F_{p,max} = 1.6S_{DS}I_pW_p = 1.6(1.487)(1.0)(W_p) = 2.379W_p$$

$$F_{p,min} = 0.3S_{DS}I_pW_p = 0.3(1.487)(1.0)(W_p) = 0.446W_p$$ (controlling equation)

$$F_p = 0.446W_p = 0.446(10{,}245\text{ lb}) = 4{,}570\text{ lb}$$ (controlling seismic design force)

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Prescribed Seismic Forces: Wall Element and Body of Wall Panel Connections

- Horizontal seismic load effect, E_h

$$Q_E = F_p = 4{,}570\text{ lb}$$

$$E_h = \rho Q_E = (1.0)(4{,}570\text{ lb}) = 4{,}570\text{ lb}$$

- Vertical seismic load effect, E_v

$$E_v = 0.2S_{DS}D = (0.2)(1.487\text{g})(10{,}245\text{ lb}) = 3{,}047\text{ lb}$$

- Basic Load Combinations for Strength Design to determine the design member and connection forces to be used in conjunction with seismic and gravity loads:

$1.2D + E_v + E_h + L + 0.2S$ (Load Combination 6)

$0.9D - E_v + E_h$ (Load Combination 7)

For nonstructural components, the terms *L* and *S* are typically zero.

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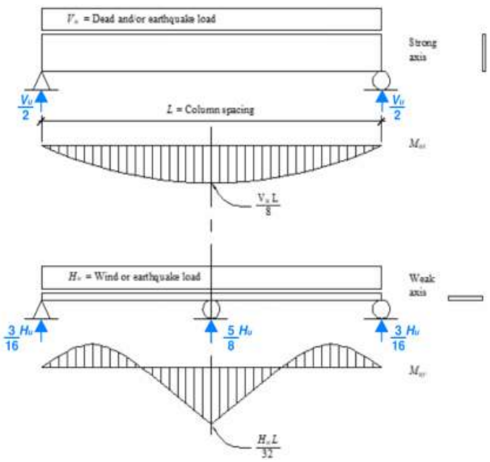
Proportioning and Design: Wall Element and Body of Wall Panel Connections



Spandrel panel bending moments

- The vertical forces, V_u, horizontal forces, H_u, and moments, M_u, are calculated using the applicable strength load combinations

Proportioning and Design: Wall Element and Body of Wall Panel Connections

- Basic Load Combination 1: $1.4D$

$V_u = 1.4D = 1.4(10{,}245 \text{ lb}) = 14{,}343 \text{ lb}$ (vertical downward force)

$M_{ux} = \frac{V_u L}{8} = \frac{(14{,}343 \text{ lb})(24 \text{ ft})}{8} = 43{,}029 \text{ lb}-\text{ft}$ (strong axis bending moment)

- Basic Load Combination 6: $1.2D + E_v + E_h + L + 0.2S$

$V_{u,max} = 1.2D + E_v = 1.2(10{,}245 \text{ lb}) + 3{,}047 \text{ lb} = 15{,}341 \text{ lb}$ (vertical downward force)

$\parallel H_u = E_h = 4{,}570 \text{ lb}$ (hor. load parallel to panel)

$\perp H_u = E_h = 4{,}570 \text{ lb}$ (hor. load perpendicular to panel)

$M_{ux,max} = \frac{V_{u,max} L}{8} = \frac{(15{,}341 \text{ lb})(24 \text{ ft})}{8} = 46{,}023 \text{ lb}-\text{ft}$ (strong axis bending moment)

$M_{uy} = \frac{H_u L}{32} = \frac{(4{,}570 \text{ lb})(24 \text{ ft})}{32} = 3{,}428 \text{ lb}-\text{ft}$ (weak axis bending moment)

Proportioning and Design: Wall Element and Body of Wall Panel Connections

- Basic Load Combination 7: $0.9D - E_v + E_h$

$V_{u,min} = 0.9D - E_v = 0.9(10{,}245 \text{ lb}) - 3{,}047 \text{ lb} = 6{,}174 \text{ lb}$ (vertical downward force)

$\parallel H_u = E_h = 4{,}570 \text{ lb}$ (horizontal load parallel to panel)

$\perp H_u = E_h = 4{,}570 \text{ lb}$ (horizontal load perp. to panel)

$M_{ux,min} = \frac{V_{u,min}L}{8} = \frac{(6{,}174 \text{ lb})(24 \text{ ft})}{8} = 18{,}521 \text{ lb–ft}$ (strong axis bending moment)

$M_{uy} = \frac{H_u L}{32} = \frac{(4{,}570 \text{ lb})(24 \text{ ft})}{32} = 3{,}428 \text{ lb–ft}$ (weak axis bending moment)

Prescribed Seismic Forces: Fasteners of the Connecting System

- The “fasteners of the connecting system” category is intended to apply to the connections with limited ductility that can have a brittle failure mechanism.
- Spandrel panel and glass weight, $W_p = D = 8{,}775 \text{ lb} + 1{,}470 \text{ lb} = 10{,}245 \text{ lb}$
- Seismic design force, F_p

$F_p = 0.4 S_{DS} I_p W_p \left[\frac{H_f}{R_\mu}\right]\left[\frac{C_{AR}}{R_{po}}\right] = 0.4(1.487)(1.0)(W_p)\left[\frac{1.74}{1.71}\right]\left[\frac{2.8}{1.5}\right] = 1.129 W_p$ (controlling equation)

$F_{p,max} = 1.6 S_{DS} I_p W_p = 1.6(1.487)(1.0)(W_p) = 2.379 W_p$

$F_{p,min} = 0.3 S_{DS} I_p W_p = 0.3(1.487)(1.0)(W_p) = 0.446 W_p$

$F_p = 1.1291 W_p = 1.129(10{,}245 \text{ lb}) = 11{,}568 \text{ lb}$ (controlling seismic design force)

For this example, F_p almost triples when compared to the spandrel panel wall element calculations.

Prescribed Seismic Forces: Fasteners of the Connecting System

- Horizontal seismic load effect, E_h

  $Q_E = F_p = 11{,}568 \text{ lb}$

  $E_h = \rho Q_E = (1.0)(11{,}568 \text{ lb}) = 11{,}568 \text{ lb}$

- Vertical seismic load effect, E_v

  $E_v = 0.2 S_{DS} D = (0.2)(1.487\text{g})(10{,}245 \text{ lb}) = 3{,}047 \text{ lb}$

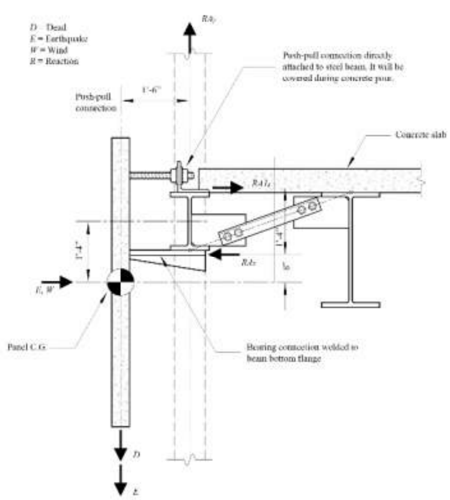
- Basic Load Combinations for Strength Design to determine the design member and connection forces to be used in conjunction with seismic and gravity loads:

  $1.2D + E_v + E_h + L + 0.2S$ (Load Combination 6)

  $0.9D - E_v + E_h$ (Load Combination 7)

  For nonstructural components, the terms *L* and *S* are typically zero.

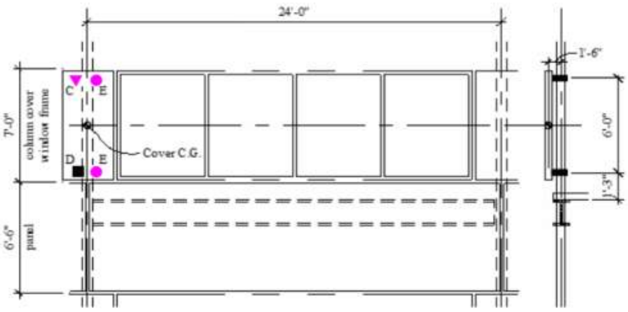
Proportioning and Design: Fasteners of the Connecting System



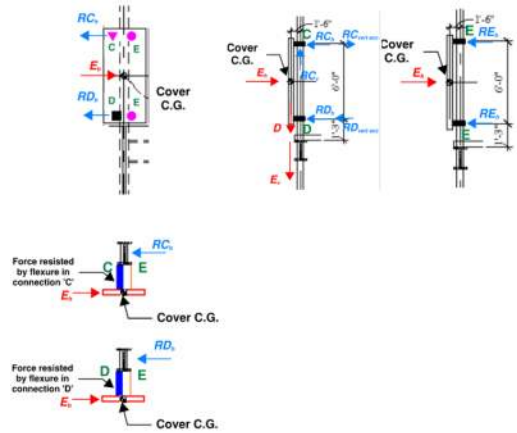
Spandrel panel connection and design forces

- Proportioning and design is determined in a similar manner as the "wall element and body of wall panel connections"
- Refer to *NEHRP Design Examples*. The vertical forces, V_u, horizontal forces, H_u, and moments, M_u, are calculated using the applicable strength load combinations.

Concrete Cover Layout and Seismic Forces



Column cover layout connection



Column cover connection forces

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Prescribed Seismic Displacements

- Calculations based on allowable story drift requirements.
- Since this is a five-story building, does not use masonry in the primary seismic force-resisting system, and it is in Risk Category II, the allowable story drift is $0.020h_{sx}$

  Story height, $h_{sx} = 13.5$ ft

  Height of upper and lower support attachment for column cover, $h_x = 47.75$ ft and $h_y = 41.75$ ft

  Seismic relative displacements, D_{pI}

  $$D_p = \frac{(h_x - h_y)\Delta_{aA}}{h_{sx}} = \frac{(47.75\text{ft} - 41.75\text{ft})(12\text{ in./ft})(0.020h_{sx})}{h_{sx}} = 1.44\text{ in.}$$

  $$D_{pI} = D_p I_e = D_p I_e = (1.44\text{ in.})(1.0) = 1.44\text{ in.}$$

- The joints at the top and bottom of the column cover must be designed to accommodate an in-plane relative displacement of 1.44 inches.

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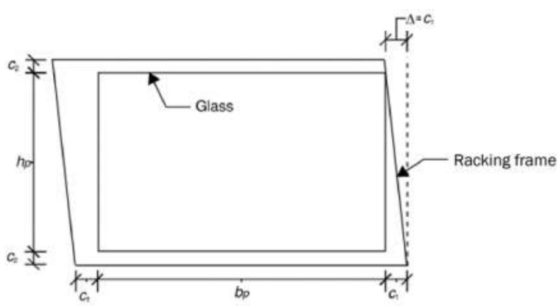
Prescribed Seismic Displacements: Accommodating Drift in Glazing

- Drift requirements for glazing are in ASCE/SEI 7-22 Section 13.5.9.
- Clearance shall be large enough so that the glass panel will not fall out of the frame as required by $\Delta_{fallout} \geq$ maximum ($1.25D_{pl}$, 0.5")
- This can be satisfied in several ways:
  - By test or engineering analysis. The test is AAMA 501.6, *Recommended Dynamic Test Method for determining the Seismic Drift Causing Glass Fallout from a Wall System* (AAMA, 2018).
  - Use fully tempered monolithic glass in Risk Category I, II, or III and less than 10 feet above a walking surface.
  - Use annealed or heat-strengthened laminated glass in single thickness with interlayer no less than 0.030 in. that is captured mechanically in a wall system glazing pocket, and whose perimeter is secured to the frame by a wet glazed gunable curing elastomeric sealant perimeter bead of ½ in. (13mm) minimum glass contact width, or other approved anchorage system.

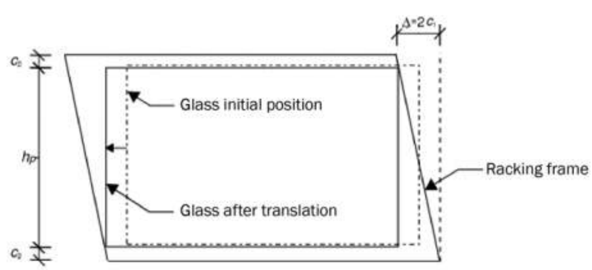
Prescribed Seismic Displacements: Accommodating Drift in Glazing

- Or the prescriptive formula of Section 13.5.9.1, Exception 1 can be used:

$$D_{clear} = 2c_1\left(1 + \frac{h_p c_2}{b_p c_1}\right) \geq 1.25\ D_{pI} = \text{maximum}\ (1.25\ D_p I_e \text{ and } 0.5")$$



Scenario 1: Glass does not move



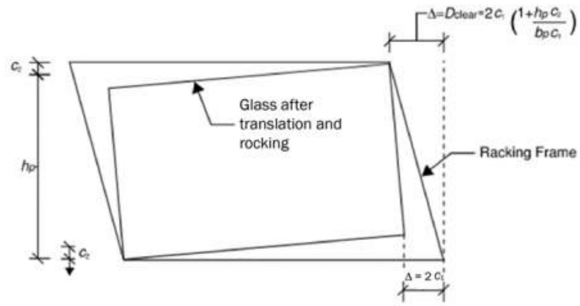
Scenario 2: Glass translates but does not rock

Prescribed Seismic Displacements: Accommodating Drift in Glazing

- Combining translating and rocking gives

  $$D_{clear} = 2c_1\left(1 + \frac{h_p c_2}{b_p c_1}\right)$$

- This assumes the toe of the glass can rotate downward. Limitations on rotation due to location and flexibility of setting blocks under the glass need to be addressed.



Scenario 3: Glass translates and rocks with vertical movement at both sill and head

Questions?

Seismic Analysis of Egress Stairs

- Prescribed seismic forces
- Prescribed seismic displacements

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Egress Stairs Description

Example Summary

- **Nonstructural components**
  Architectural – egress stairways not part of the building seismic force-resisting system
  Architectural – egress stair and ramp fasteners and attachments
- **Building seismic force-resisting systems**
  East–west direction: steel special concentrically braced frames
  North–south direction: steel special moment frames
- **Equipment support:** Not applicable
- **Occupancy:** Emergency medical facility
- **Risk Category:** IV
- **Component Importance Factor:** $I_p = 1.5$
- **Number of stories:** 5
- $S_{DS} = 1.00$

- Calculations for flight of stairs and landing between Level 3 and Level 4
- Effective dead load: 25 psf
- Design live load: 100 psf

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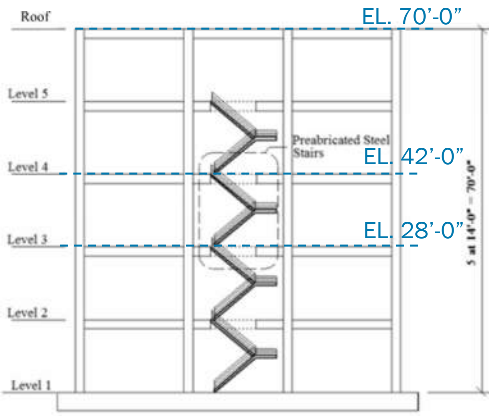
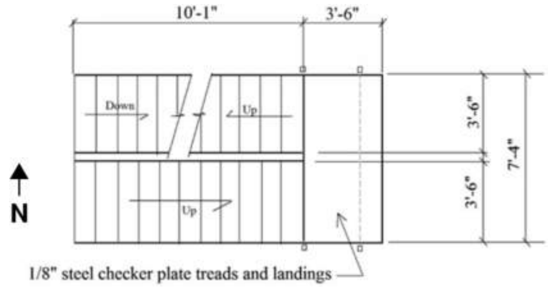
Egress Stairs Description



Elevation of egress stairs



Plan of egress stairs

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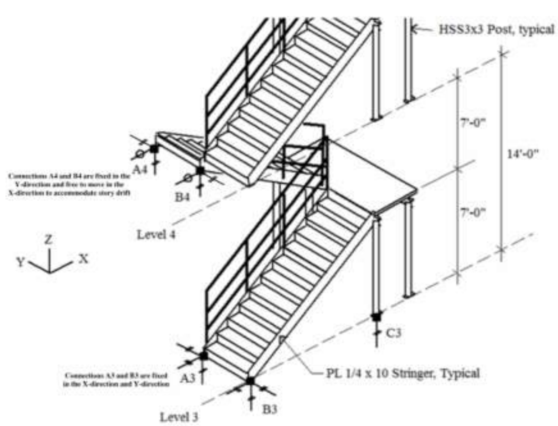
ASCE/SEI 7-22 Parameters and Coefficients



Isometric view of egress stairs

Coefficients for Architectural Components (Table 13.5-1)

- Egress stairways not part of the building seismic force-resisting system:
  - $C_{AR} = 1.0$
  - $R_{po} = 1.5$
  - $\Omega_{0p} = 2.0$
- Egress stairs and ramp fasteners and attachments:
  - $C_{AR} = 2.2$
  - $R_{po} = 1.5$
  - $\Omega_{0p} = 1.75$

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ASCE/SEI 7-22 Parameters and Coefficients

- Design coefficients and factors for seismic force-resisting systems (Table 12.2-1)
  - E-W direction – steel SCBF: $R = 6.0$ and $\Omega_0 = 2.0$
  - N-S direction – steel SMRF: $R = 8.0$ and $\Omega_0 = 3.0$
- Short period design spectral acceleration, $S_{DS} = 1.00$
- Seismic Importance Factor, $I_e = 1.5$
- Component Importance Factor, $I_p = 1.5$
- Redundancy factor, $\rho = 1.0$
- Average height of attachments, $z = 35\text{ ft}$
- Average roof height, $h = 70\text{ ft}$
- Story height, $h_{sx} = 14\text{ ft}$

ASCE/SEI 7-22 Parameters and Coefficients

- Stair flight weight, $W_p = \left(20\,\frac{\text{lb}}{\text{ft}^2}\right)(10.083\text{ ft long})(3.5\text{ ft wide}) = 706\text{ lb}$
- Stair landing weight, $W_p = \left(20\,\frac{\text{lb}}{\text{ft}^2}\right)(7.333\text{ ft long})(3.5\text{ ft wide}) = 513\text{ lb}$

- Approximate fundamental period of the supporting structure, T_a (Section 12.8.2.1)
  - E-W direction – steel SCBF: $T_a = C_t {h_n}^x = (0.02)(70\text{ ft})^{0.75} = 0.484\text{ s}$
  - N-S direction – steel SMRF: $T_a = C_t {h_n}^x = (0.028)(70\text{ ft})^{0.8} = 0.838\text{ s}$

  Per Section 13.3.1.1, for structures with combinations of seismic force-resisting systems, the lowest value of T_a shall be used. For this example, $T_a = 0.484\text{ s}$ controls.

ASCE/SEI 7-22 Parameters and Coefficients

- Force amplification factor as a function of height in the structure, H_f

$$a_1 = \frac{1}{T_a} = \frac{1}{0.484\text{ s}} = 2.07 \leq 2.5$$

$$a_2 = [1 - (0.4/T_a)^2] = [1 - (0.4/0.484\text{ s})^2] = 0.32 \geq 0$$

$$H_f = 1 + a_1\left(\frac{z}{h}\right) + a_2\left(\frac{z}{h}\right)^{10} = 1 + 2.07\left(\frac{35\text{ ft}}{70\text{ ft}}\right) + 0.32\left(\frac{35\text{ ft}}{70\text{ ft}}\right)^{10} = 2.03$$

- Structure ductility reduction factor, R_μ

$$R_\mu = (1.1\,R/(I_e\Omega_0))^{1/2} \geq 1.3$$

  - E-W direction – steel SCBF: $R_\mu = (1.1(6/((1.5)(2)))^{1/2} = 1.48 \geq 1.3$
  - N-S direction – steel SMRF: $R_\mu = (1.1(8/((1.5)(3)))^{1/2} = 1.40 \geq 1.3$

Per Section 13.3.1.2, if the structure contains a combination of seismic force-resisting systems in different directions, the lowest value of R_μ shall be used. For this example, $R_\mu = 1.40$ controls.

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Applicable Requirements

- Supports, attachments, and the egress stairs themselves shall be designed to meet the seismic requirements of Chapter 13 (Section 13.2.1).
- Component failure shall not cause failure of an essential architectural, mechanical, or electrical component (Section 13.2.4).
- Seismic attachments shall be bolted, welded, or otherwise positively fastened without considering the frictional resistance produced by the effects of gravity (Section 13.4).
- F_p shall be applied at the component's center of gravity and distributed relative to the component's mass distribution (Section 13.3.1).
- Effects of seismic relative displacements shall be considered in combination with displacements caused by other loads as appropriate (Section 13.3.2).

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Applicable Requirements (Continued)

- The net relative displacement shall be assumed to occur in any horizontal direction, and it shall be accommodated through slotted or sliding connections, or metal supports designed with rotation capacity to accommodate D_{pI} (Section 13.5.10).
- Sliding connections with slotted or oversize holes, sliding bearing supports with restraints that engage after the displacement, D_{pI}, is exceeded, and connections that permit movement by deformation of metal attachments, shall accommodate a displacement D_{pI}, but not less than 0.5 in. (13 mm), without loss of vertical support or inducement of displacement-related compression forces in the stair (Section 13.5.10).
- The strength of the supports shall not be limited by bolt shear, weld fracture, or other limit states with lesser ductility (Section 13.5.10).

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Prescribed Seismic Forces: Egress Stairways not Part of the Building Seismic Force-Resisting System

Flight of Stairs

- Component weight, $W_p = D = 706 \text{ lb}$
- Seismic design force, F_p

$$F_p = 0.4 S_{DS} I_p W_p \left[\frac{H_f}{R_\mu}\right]\left[\frac{C_{AR}}{R_{po}}\right] = 0.4(1.0)(1.5)(W_p)\left[\frac{2.03}{1.40}\right]\left[\frac{1.0}{1.5}\right] = 0.582 W_p \quad \text{(controlling equation)}$$

$$F_{p,max} = 1.6 S_{DS} I_p W_p = 1.6(1.0)(1.5)(W_p) = 2.4 W_p$$

$$F_{p,min} = 0.3 S_{DS} I_p W_p = 0.3(1.0)(1.5)(W_p) = 0.45 W_p$$

$$F_p = 0.582 W_p = 0.582(706 \text{ lb}) = 410 \text{ lb} \quad \text{(controlling seismic design force)}$$

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Prescribed Seismic Forces:
Egress Stairways not Part of the Building Seismic Force-Resisting System

Flight of Stairs (Continued)

- Horizontal seismic load effect, E_h

  $Q_E = F_p = 410 \text{ lb}$

  $E_h = \rho Q_E = (1.0)(335 \text{ lb}) = 410 \text{ lb}$

- Vertical seismic load effect, E_v

  $E_v = 0.2 S_{DS} D = (0.2)(1.0\text{g})(706 \text{ lb}) = 141 \text{ lb}$

- Basic Load Combinations for Strength Design to determine the design member and connection forces to be used in conjunction with seismic and gravity loads:

  $1.2D + E_v + E_h + L + 0.2S$ (Load Combination 6)

  $0.9D - E_v + E_h$ (Load Combination 7)

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Prescribed Seismic Forces:
Egress Stairways not Part of the Building Seismic Force-Resisting System

Landing

- Component weight, $W_p = D = 513 \text{ lb}$
- Seismic design force, F_p

  $F_p = 0.4 S_{DS} I_p W_p \left[\frac{H_f}{R_\mu}\right]\left[\frac{C_{AR}}{R_{po}}\right] = 0.4(1.0)(1.5)(W_p)\left[\frac{2.03}{1.40}\right]\left[\frac{1.0}{1.5}\right] = 0.582 W_p$ (controlling equation)

  $F_{p,max} = 1.6 S_{DS} I_p W_p = 1.6(1.0)(1.5)(W_p) = 2.4 W_p$

  $F_{p,min} = 0.3 S_{DS} I_p W_p = 0.3(1.0)(1.5)(W_p) = 0.45 W_p$

  $F_p = 0.582 W_p = 0.582(513 \text{ lb}) = 298 \text{ lb}$ (controlling seismic design force)

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Prescribed Seismic Forces:
Egress Stairways not Part of the Building Seismic Force-Resisting System

Landing (Continued)

- Horizontal seismic load effect, E_h

  $Q_E = F_p = 298 \text{ lb}$

  $E_h = \rho Q_E = (1.0)(298 \text{ lb}) = 298 \text{ lb}$

- Vertical seismic load effect, E_v

  $E_v = 0.2 S_{DS} D = (0.2)(1.0\text{g})(513 \text{ lb}) = 103 \text{ lb}$

- Basic Load Combinations for Strength Design to determine the design member and connection forces to be used in conjunction with seismic and gravity loads:

  $1.2D + E_v + E_h + L + 0.2S$ (Load Combination 6)

  $0.9D - E_v + E_h$ (Load Combination 7)

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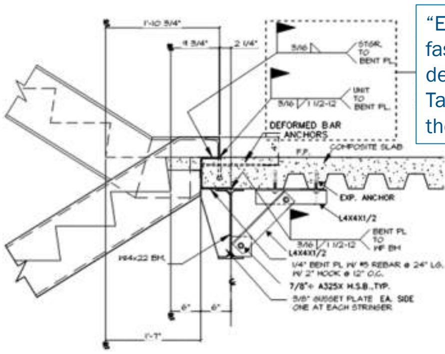
Increased Seismic Forces for Fasteners and Attachments



"Egress stair and ramp fasteners and attachments" definition in ASCE/SEI 7-22 Table 13.5-1 only applies at these connections.

Connection of stair to primary structure

- The attachment to the primary structure is not well delimited to the rest of the egress stairway connections.
- It is recommended to apply the increased design forces in attachments with a nonductile failure mechanism.

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Prescribed Seismic Forces: Egress Stairs and Ramp Fasteners and Attachments

Flight of Stairs

- Component weight, $W_p = D = 706 \text{ lb}$
- Seismic design force, F_p

$$F_p = 0.4 S_{DS} I_p W_p \left[\frac{H_f}{R_\mu}\right]\left[\frac{C_{AR}}{R_{po}}\right] = 0.4(1.0)(1.5)(W_p)\left[\frac{2.03}{1.40}\right]\left[\frac{2.2}{1.5}\right] = 1.280 W_p \quad \text{(controlling equation)}$$

$$F_{p,max} = 1.6 S_{DS} I_p W_p = 1.6(1.0)(1.5)(W_p) = 2.4 W_p$$

$$F_{p,min} = 0.3 S_{DS} I_p W_p = 0.3(1.0)(1.5)(W_p) = 0.45 W_p$$

$$F_p = 1.280 W_p = 1.280(706 \text{ lb}) = 903 \text{ lb} \quad \text{(controlling seismic design force)}$$

- Compare increased design force, $F_p = 903$ lb for fasteners and attachments, against $F_p = 410$ lb for design of rest of egress stairs.

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Prescribed Seismic Forces: Egress Stairs and Ramp Fasteners and Attachments

Landing

- Component weight, $W_p = D = 513 \text{ lb}$
- Seismic design force, F_p

$$F_p = 0.4 S_{DS} I_p W_p \left[\frac{H_f}{R_\mu}\right]\left[\frac{C_{AR}}{R_{po}}\right] = 0.4(1.0)(1.5)(W_p)\left[\frac{2.03}{1.40}\right]\left[\frac{2.2}{1.5}\right] = 1.280 W_p \quad \text{(controlling equation)}$$

$$F_{p,max} = 1.6 S_{DS} I_p W_p = 1.6(1.0)(1.5)(W_p) = 2.4 W_p$$

$$F_{p,min} = 0.3 S_{DS} I_p W_p = 0.3(1.0)(1.5)(W_p) = 0.45 W_p$$

$$F_p = 1.280 W_p = 1.280(513 \text{ lb}) = 657 \text{ lb} \quad \text{(controlling seismic design force)}$$

- Compare increased design force, $F_p = 657$ lb for fasteners and attachments, against $F_p = 298$ lb for design of rest of egress stairs.

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Prescribed Seismic Displacements

- Calculations based on allowable story drift requirements.
- Since this is a five-story building, does not use masonry in the primary seismic force-resisting system, and it is in Risk Category IV, the allowable story drift is $0.010h_{sx}$.

  Story height, $h_{sx} = 14\text{ ft}$

  Height of upper and lower support attachment, $h_x = 42\text{ ft}$ and $h_y = 28\text{ ft}$

  Seismic relative displacements, D_{pI}

  $$D_p = \frac{(h_x - h_y)\Delta_{aA}}{h_{sx}} = \frac{(42\text{ft} - 28\text{ft})(12\text{ in./ft})(0.010h_{sx})}{h_{sx}} = 1.68\text{ in.}$$

  $$D_{pI} = D_p I_e = (1.68\text{ in.})(1.5) = 2.52\text{ in.}$$
- The displacement can act in any direction, so the connection must be able to accommodate a total range of movement of two times D_{pI}, or $2 \times D_{pI} = 5.04\text{ in.}$ in all directions.

Stairway Design Load Combinations

- The egress stairway and connections should be designed for the linear combination:

  Design Load Combination = Inertial Force Demand + Displacement-Induced Demand
- For this example, the following load combinations would be required in the analysis:

  $EQX = \pm F_{pX}$

  $EQY = \pm F_{pY} \pm EQY_{drift}$
- The unrestrained connection in the X-direction (longitudinal direction) and the induced demand at the fixed connection in the Y-direction (transverse direction) at Level 4 shall be able to accommodate the story drift, and the seismic relative displacements.

Questions?

HVAC Fan Unit Support

- Case 1: Direct attachment to structure
- Case 2: Support on vibration isolation springs

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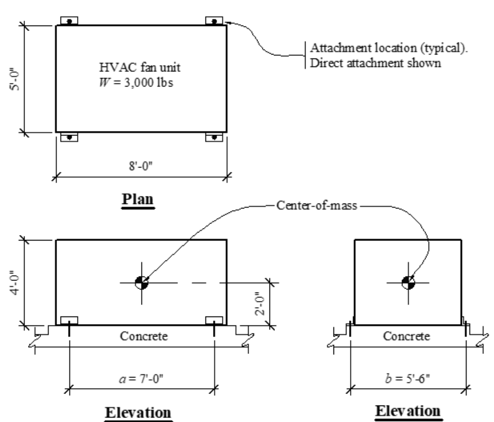
HVAC Fan Unit Support Description

Example Summary

- **Nonstructural components**
  Case 1: Mechanical and electrical – HVAC fan unit
  Case 2: Mechanical and electrical – spring-isolated component
- **Building seismic force-resisting system:** Ordinary reinforced masonry shear wall (bearing wall system)
- **Equipment support:** Integral
- **Occupancy:** Office
- **Risk Category:** II
- **Component Importance Factor:** $I_p = 1.0$
- **Number of stories:** 3
- $S_{DS} = 0.474$

- 4-foot high, 5-foot-wide, 8-foot-long, 3,000-pound HVAC fan unit that is supported on two long sides near each corner
- 4,000 psi normalweight concrete roof slab
- Three-story office building. All stories are 12-feet tall.

HVAC Fan Unit Support Description



HVAC Fan Unit

- **Case 1:** Direct attachment to the structure using 36 ksi, carbon steel, cast-in place anchors
- **Case 2:** Support on vibration isolation springs that are attached to the slab with 36 ksi, carbon steel, post-installed expansion anchors. The nominal gap between the vibration spring seismic restraints and the base frame of the fan unit is presumed to be greater than 0.25 in.

ASCE/SEI 7-22 Parameters and Coefficients

Coefficients for Mechanical and Electrical Components (Table 13.6-1)

- Air-side HVACR, fans, air handlers, air conditioning units, cabinet heaters, air distribution boxes, and other mechanical components constructed of sheet metal framing:
  - $C_{AR} = 1.4$
  - $R_{po} = 2.0$
  - $\Omega_{0p} = 2.0$
- Spring-isolated components and systems and vibration-isolated floors closely restrained using built-in or separate elastomeric snubbing devices or resilient perimeter stops:
  - $C_{AR} = 2.2$
  - $R_{po} = 1.3$
  - $\Omega_{0p} = 1.75$

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ASCE/SEI 7-22 Parameters and Coefficients

- Design coefficients and factors for seismic force-resisting system (Table 12.2-1)

  Bearing wall system – ordinary reinforced masonry shear wall: $R = 2.0$ and $\Omega_0 = 2.5$
- Short period design spectral acceleration, $S_{DS} = 0.474$
- Seismic Importance Factor, $I_e = 1.0$
- Component Importance Factor, $I_p = 1.0$
- Redundancy factor, $\rho = 1.0$
- Height of attachment at roof, $z = 36\ \text{ft}$
- Average roof height, $h = 36\ \text{ft}$

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ASCE/SEI 7-22 Parameters and Coefficients

- HVAC fan unit weight, $W_p = 3{,}000\ \text{lb}$
- Approximate fundamental period of the supporting structure, T_a (Section 12.8.2.1)

  Ordinary reinforced masonry shear walls (all other structural systems, per Table 12.8-2):

  $h_n = h = 36\ \text{ft}$

  $C_t = 0.02$

  $x = 0.75$

  $T_a = C_t {h_n}^x = (0.02)(36\ \text{ft})^{0.75} = 0.29\ \text{s}$

ASCE/SEI 7-22 Parameters and Coefficients

- Force amplification factor as a function of height in the structure, H_f

  $a_1 = \frac{1}{T_a} = \frac{1}{0.29\ \text{s}} = 3.45 > 2.5$, use $a_1 = 2.5$

  $a_2 = [1 - (0.4/T_a)^2] = [1 - (0.4/0.29\ \text{s})^2] = -0.90 < 0$, use $a_2 = 0$

  $H_f = 1 + a_1 \left(\frac{z}{h}\right) + a_2 \left(\frac{z}{h}\right)^{10} = 1 + 2.5 \left(\frac{36\ \text{ft}}{36\ \text{ft}}\right) + 0 \left(\frac{36\ \text{ft}}{36\ \text{ft}}\right)^{10} = 3.5$

  For supporting structures with $T_a \leq 0.4$ s, the parameters a_1 and a_2 are controlled by their limits, i.e., $a_1 = 2.5$ and $a_2 = 0$.
- Structure ductility reduction factor, R_μ

  $R_\mu = (1.1\, R/(I_e \Omega_0))^{1/2} = (1.1(2/((1.0)(2.5)))^{1/2} = 0.94 < 1.3$, use $R_\mu = 1.3$

Applicable Requirements

- Component failure shall not cause failure of an essential architectural, mechanical, or electrical component (Section 13.2.4).
- Seismic attachments shall be bolted, welded, or otherwise positively fastened without considering the frictional resistance produced by the effects of gravity (Section 13.4).
- F_p shall be applied at the component's center of gravity and distributed relative to the component's mass distribution (Section 13.3.1).
- Attachments to concrete or masonry shall be designed to resist the seismic load effects including overstrength, Ω_0 shall be taken as Ω_{0p} (Section 13.4.2).
- Exterior nonstructural wall panels or elements that are attached to or enclose the structure shall be designed to accommodate the seismic relative displacements, and movements caused by temperature changes (Section 13.5.3).

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Applicable Requirements (Continued)

- Attachments and supports transferring seismic loads shall be constructed of materials suitable for the application and must be designed and constructed in accordance with a nationally recognized structural standard (Section 13.6.4.4).
- Components mounted on vibration isolation systems shall have a bumper restraint or snubber in each horizontal direction. Vertical restraints must be provided where required to resist overturning. Isolator housings and restraints must also be constructed of ductile materials. A viscoelastic pad, or similar material of appropriate thickness, must be used between the bumper and equipment item to limit the impact load. **Such components also must resist doubled seismic design forces if the nominal clearance (air gap) between the equipment support frame and restraints is greater than 0.25 in.** (Section 13.6.4.5 and Table 13.6-1, Footnote a).

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Prescribed Seismic Forces: Case 1: Direct Attachment to Structure

- HVAC fan unit weight, $W_p = D = 3{,}000 \text{ lb}$
- Seismic design force, F_p

$$F_p = 0.4S_{DS}I_pW_p\left[\frac{H_f}{R_\mu}\right]\left[\frac{C_{AR}}{R_{po}}\right] = 0.4(0.474)(1.0)(W_p)\left[\frac{3.5}{1.3}\right]\left[\frac{1.4}{2.0}\right] = 0.357W_p \text{ (controlling equation)}$$

$$F_{p,max} = 1.6S_{DS}I_pW_p = 1.6(0.474)(1.0)(W_p) = 0.758W_p$$

$$F_{p,min} = 0.3S_{DS}I_pW_p = 0.3(0.474)(1.0)(W_p) = 0.142W_p$$

$$F_p = 0.357W_p = 0.357(3{,}000 \text{ lb}) = 1{,}072 \text{ lb} \qquad \text{(controlling seismic design force)}$$

Prescribed Seismic Forces: Case 1: Direct Attachment to Structure

- Horizontal seismic load effect, E_h

$$Q_E = F_p = 1{,}072 \text{ lb}$$

$$E_h = \rho Q_E = (1.0)(1{,}072 \text{ lb}) = 1{,}072 \text{ lb}$$

- Vertical seismic load effect, E_v

$$E_v = 0.2S_{DS}D = (0.2)(0.474\text{g})(3{,}000 \text{ lb}) = 284 \text{ lb}$$

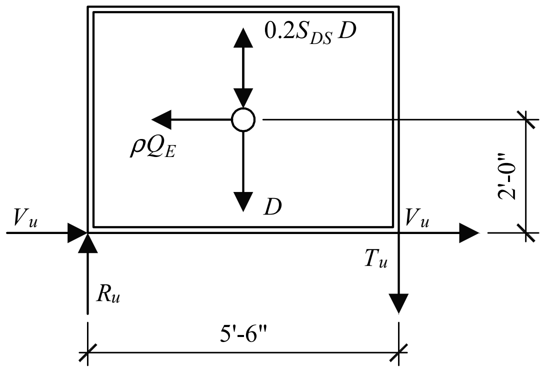
- Basic Load Combinations for Strength Design to determine the design member and connection forces to be used in conjunction with seismic loads:

$$1.2D + E_v + E_h + L + 0.2S \qquad \text{(Load Combination 6)}$$

$$0.9D - E_v + E_h \qquad \text{(Load Combination 7)}$$

For nonstructural components, the terms *L* and *S* are typically zero.

Proportioning and Design: Case 1: Direct Attachment to Structure



Free-body diagram for seismic force analysis

- Seismic load effects are used to determine bolt shear, V_u, and tension, T_u (where a negative value indicates tension)
- Signs of E_v and E_h are selected to result in the largest value of T_u

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Proportioning and Design: Case 1: Direct Attachment to Structure

- Basic Load Combination 6: $1.2D + E_v + E_h + L + 0.2S$

$$V_u = \frac{E_h}{4\text{ bolts}} = \frac{1{,}072\text{ lb}}{4\text{ bolts}} = 268\text{ lb/bolt}$$

$$T_u = \frac{(1.2D - E_v)(5.5/2\text{ ft}) - (E_h)(2\text{ ft})}{(5.5\text{ ft})(2\text{ bolts})} = \frac{(1.2(3{,}000\text{ lb}) - 284\text{ lb})(5.5/2\text{ ft}) - (1{,}072\text{ lb})(2\text{ ft})}{(5.5\text{ ft})(2\text{ bolts})} = 634\text{ lb/bolt} \quad \text{(no tension)}$$

- Basic Load Combination 6: $0.9D - E_v + E_h$

$$V_u = \frac{E_h}{4\text{ bolts}} = \frac{1{,}072\text{ lb}}{4\text{ bolts}} = 268\text{ lb/bolt}$$

$$T_u = \frac{(0.9D - E_v)(5.5/2\text{ ft}) - (E_h)(2\text{ ft})}{(5.5\text{ ft})(2\text{ bolts})} = \frac{(0.9(3{,}000\text{ lb}) - 284\text{ lb})(5.5/2\text{ ft}) - (1{,}072\text{ lb})(2\text{ ft})}{(5.5\text{ ft})(2\text{ bolts})} = 409\text{ lb/bolt} \quad \text{(no tension)}$$

- Anchors with design capacities exceeding the calculated demands would be selected using ACI 318 Chapter 17.

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Prescribed Seismic Forces:
Case 2: Support on Vibration Isolation Springs

- HVAC fan unit weight, $W_p = D = 3{,}000 \text{ lb}$
- Seismic design force, F_p

$$F_p = 0.4S_{DS}I_pW_p\left[\frac{H_f}{R_\mu}\right]\left[\frac{C_{AR}}{R_{po}}\right] = 0.4(0.474)(1.0)(W_p)\left[\frac{3.5}{1.3}\right]\left[\frac{2.2}{1.3}\right] = 0.864W_p$$

$$F_{p,max} = 1.6S_{DS}I_pW_p = 1.6(0.474)(1.0)(W_p) = 0.758W_p$$ (controlling equation)

$$F_{p,min} = 0.3S_{DS}I_pW_p = 0.3(0.474)(1.0)(W_p) = 0.142W_p$$

$$F_p = 0.758W_p = 0.758(3{,}000 \text{ lb}) = 2{,}275 \text{ lb}$$ (controlling seismic design force)

Prescribed Seismic Forces:
Case 2: Support on Vibration Isolation Springs

- Per Table 13.6-1 Footnote a, the design force should be taken as $2F_p$ if nominal clearance (air gap) between equipment and seismic restraint is greater than 0.25 in.
- Horizontal seismic load effect, E_h

$$Q_E = 2F_p = 2(2{,}275 \text{ lb}) = 4{,}550 \text{ lb}$$

$$E_h = \rho Q_E = (1.0)(4{,}550 \text{ lb}) = 4{,}550 \text{ lb}$$

- Vertical seismic load effect, E_v

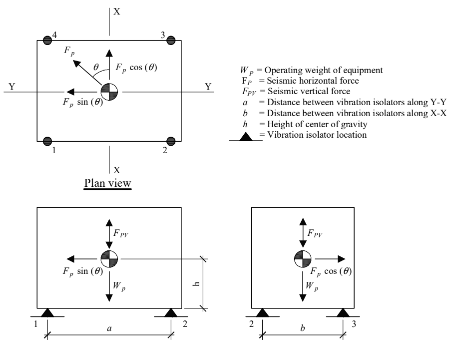
$$E_v = 0.2S_{DS}D = (0.2)(0.474\text{g})(3{,}000 \text{ lb}) = 284 \text{ lb}$$

- Basic Load Combinations for Strength Design to determine the design member and connection forces to be used in conjunction with seismic loads:

$$1.2D + E_v + E_h + L + 0.2S$$ (Load Combination 6)

$$0.9D - E_v + E_h$$ (Load Combination 7)

Proportioning and Design: Case 2: Support on Vibration Isolation Springs



ASHRAE diagonal analysis for vibration isolation springs

- The seismic load effects are used to determine the bolt shear, V_u, and tension, T_u (negative value indicates tension).
- Design forces are determined by an analysis of earthquake forces applied in a diagonal horizontal direction.
- ASHRAE A56 equations are used to estimate these demands.

Angle of diagonal bending, $\theta = \tan^{-1}\left(\frac{b}{a}\right)$

For this example, $\theta = \tan^{-1}\left(\frac{5.5 \text{ ft}}{7.0 \text{ ft}}\right) = 38.16°$

Tension per isolator, $T_u = \frac{W_p - F_{pv}}{4} - \frac{F_p h}{2}\left(\frac{\cos\theta}{b} + \frac{\sin\theta}{a}\right)$

Compression per isolator, $C_u = \frac{W_p + F_{pv}}{4} + \frac{F_p h}{2}\left(\frac{\cos\theta}{b} + \frac{\sin\theta}{a}\right)$

Shear per isolator, $V_u = \frac{F_p}{4}$

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Proportioning and Design: Case 2: Support on Vibration Isolation Springs

- Basic Load Combination 6: $1.2D + E_v + E_h + L + 0.2S$

$$T_u = \frac{1.2D - E_v}{4} - \frac{E_h h}{2}\left(\frac{\cos\theta}{b} + \frac{\sin\theta}{a}\right) = \frac{1.2(3{,}000 \text{ lb}) - 284 \text{ lb}}{4} - \frac{(4{,}550 \text{ lb})(2 \text{ ft})}{2}\left(\frac{\cos(38.16°)}{5.5 \text{ ft}} + \frac{\sin(38.16°)}{7 \text{ ft}}\right) = -223 \text{ lb}$$

$$C_u = \frac{1.2D + E_v}{4} + \frac{E_h h}{2}\left(\frac{\cos\theta}{b} + \frac{\sin\theta}{a}\right) = \frac{1.2(3{,}000 \text{ lb}) + 284 \text{ lb}}{4} + \frac{(4{,}550 \text{ lb})(2 \text{ ft})}{2}\left(\frac{\cos(38.16°)}{5.5 \text{ ft}} + \frac{\sin(38.16°)}{7 \text{ ft}}\right) = 2{,}023 \text{ lb}$$

$$V_u = \frac{E_h}{4} = \frac{4{,}550 \text{ lb}}{4} = 1{,}138 \text{ lb}$$

- Basic Load Combination 6: $1.2D + E_v + E_h + L + 0.2S$

$$T_u = \frac{0.9D - E_v}{4} - \frac{E_h h}{2}\left(\frac{\cos\theta}{b} + \frac{\sin\theta}{a}\right) = \frac{0.9(3{,}000 \text{ lb}) - 284 \text{ lb}}{4} - \frac{(4{,}550 \text{ lb})(2 \text{ ft})}{2}\left(\frac{\cos(38.16°)}{5.5 \text{ ft}} + \frac{\sin(38.16°)}{7 \text{ ft}}\right) = -448 \text{ lb}$$

$$C_u = \frac{0.9D + E_v}{4} + \frac{E_h h}{2}\left(\frac{\cos\theta}{b} + \frac{\sin\theta}{a}\right) = \frac{0.9(3{,}000 \text{ lb}) + 284 \text{ lb}}{4} + \frac{(4{,}550 \text{ lb})(2 \text{ ft})}{2}\left(\frac{\cos(38.16°)}{5.5 \text{ ft}} + \frac{\sin(38.16°)}{7 \text{ ft}}\right) = 1{,}798 \text{ lb}$$

$$V_u = \frac{E_h}{4} = \frac{4{,}550 \text{ lb}}{4} = 1{,}138 \text{ lb}$$

- The vibration isolator would be designed to resist these forces.

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Proportioning and Design: Case 2: Support on Vibration Isolation Springs

- There is no component or a support that undergoes ductile yielding at a load level less than the design strength of the corresponding anchor.
- The Basic Load Combination 7 including Ω_{0p} is applied to obtain the controlling vertical design tension force.

Tension per isolator:

$$T_u = \frac{0.9D - E_v}{4} - \frac{\Omega_{0p} E_h h}{2}\left(\frac{\cos\theta}{b} + \frac{\sin\theta}{a}\right) =$$

$$T_u = \frac{0.9(3{,}000\text{ lb}) - 284\text{ lb}}{4} - \frac{(1.75)(4{,}550\text{ lb})(2\text{ ft})}{2}\left(\frac{\cos(38.16°)}{5.5\text{ ft}} + \frac{\sin(38.16°)}{7\text{ ft}}\right) = -1{,}237\text{ lb}$$

Acting concurrently with tension, the horizontal design shear force is:

$$V_u = \frac{\Omega_{0p} E_h}{4} = \frac{(1.75)(4{,}550\text{ lb})}{4} = 1{,}991\text{ lb}$$

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Proportioning and Design: Case 2: Support on Vibration Isolation Springs

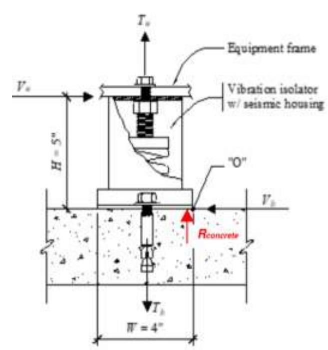
- Horizontal shear force applied at the top of the isolator generates a moment that induces prying action, which will increase the tension on the anchor.
- Each isolator is attached to the concrete slab with two anchors.
- Tension force per anchor including prying effects, T_b:

$$T_b = \frac{T_u}{2\text{ anchors}} - \left(\frac{5\text{ in.}}{2\text{ in.}}\right)\left(\frac{V_u}{2\text{ anchors}}\right)$$

$$T_b = \frac{-1{,}237\text{ lb}}{2\text{ anchors}} - \left(\frac{5\text{ in.}}{2\text{ in.}}\right)\left(\frac{1{,}991\text{ lb}}{2\text{ anchors}}\right) = -3{,}107\text{ lb}$$

- Design shear force per bolt, V_b :

$$V_b = \frac{V_u}{2\text{ anchors}} = \frac{1{,}991\text{ lb}}{2\text{ anchors}} = 995\text{ lb}$$



Anchor and snubber loads for support on vibration isolation springs

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Questions?

Piping System Seismic Design

- Piping system design
- Pipe supports and bracing
- Prescribed seismic displacements

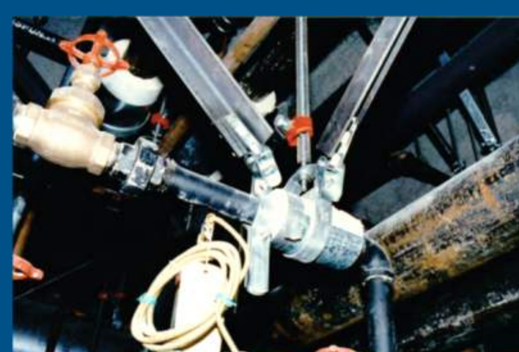


Image from FEMA E-74 (2012) Figure 6.4.3.1-5 (courtesy of Mason Industries)

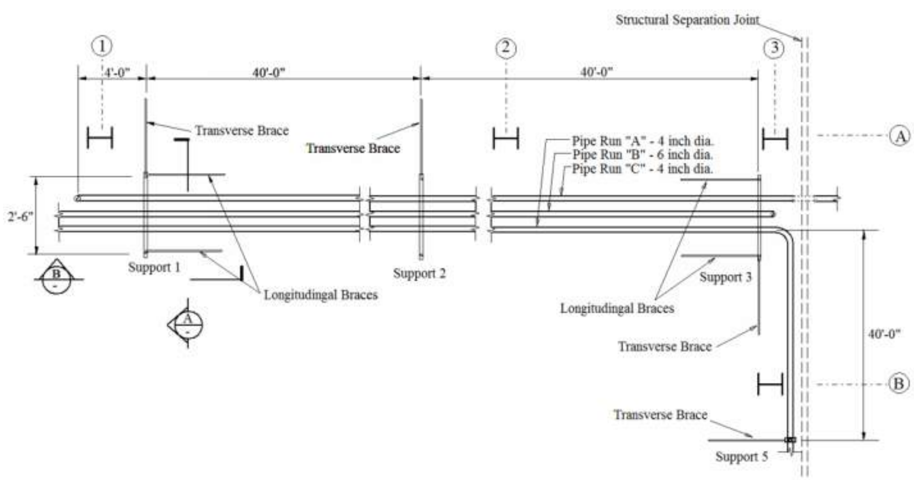
Piping System Description

Example Summary

- **Nonstructural components:** Mechanical and electrical – piping not in accordance with ASME B31 with threaded joints
- **Building seismic force-resisting system:** Steel buckling-restrained braced frames
- **Equipment support:** Distribution system supports – distribution system supports using hot-rolled steel bracing
- **Occupancy:** Acute care hospital
- **Risk Category:** IV
- **Component Importance Factor:** $I_p = 1.5$
- **Number of stories:** 2
- $S_{DS} = 1.00$

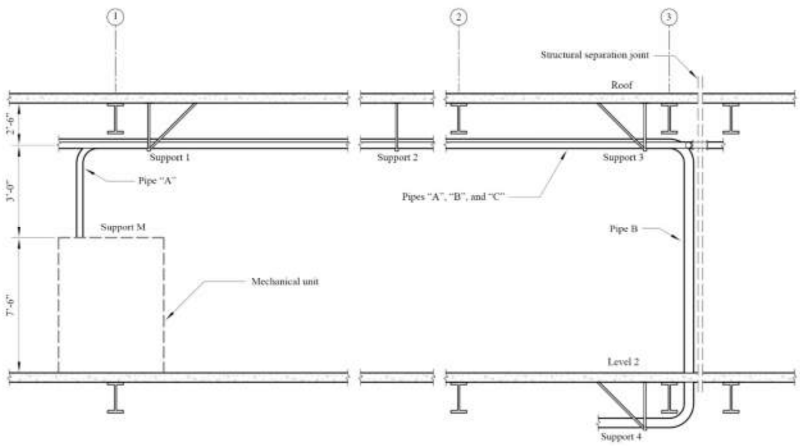
- Three piping runs of a chilled water piping system supported from the roof.
- The system is not intended to meet the ASME B31 requirements.
- One run of the piping system crosses a seismic separation joint to enter an adjacent structure.

Piping System Description



Plan of piping system

Piping System Description



Piping system near column line 'A'

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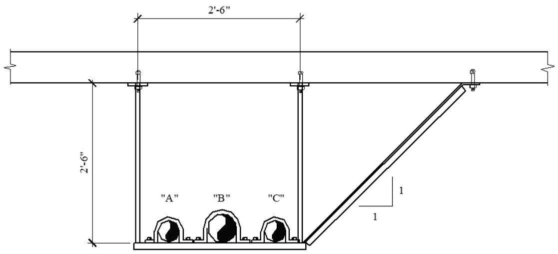
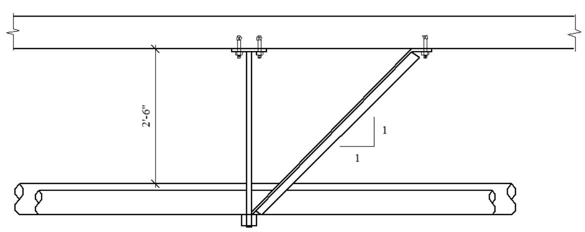
Piping System Description: Bracing



Typical trapeze-type support assembly with transverse bracing



Typical trapeze-type support assembly with longitudinal bracing

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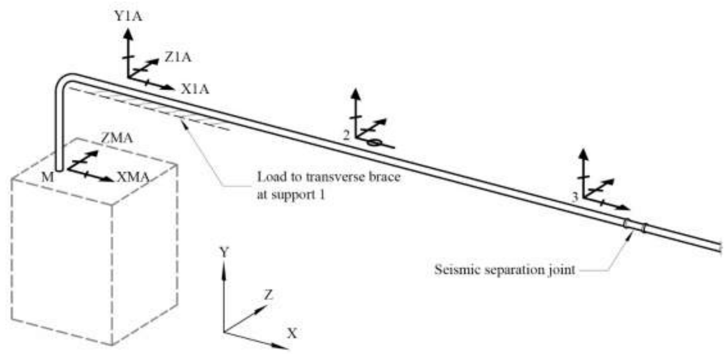
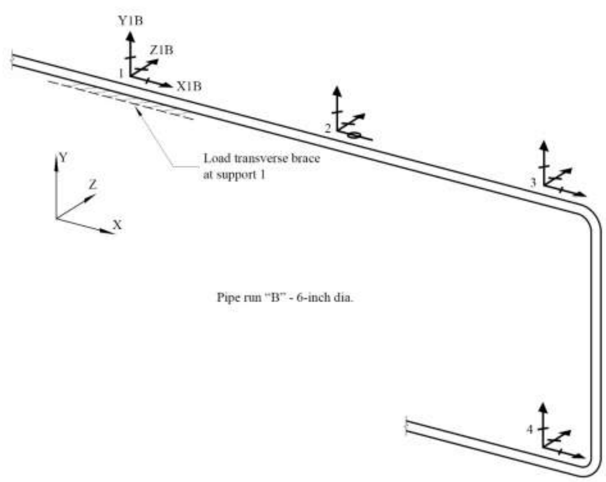
Piping System Description: System Configuration



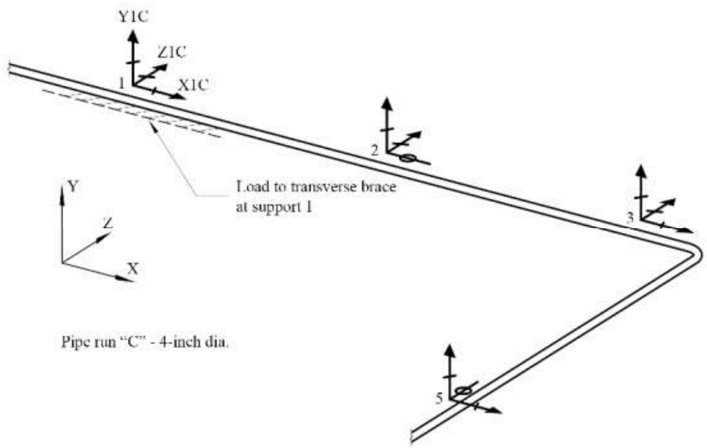
Piping Run "A": a 4-inch-diameter pipe, which connects to a large mechanical unit at Line 1 supported at the second level. It crosses a seismic separation between adjacent structures at Line 3.

Piping System Description: System Configuration



Piping Run "B": a 6-inch-diameter pipe, which has a vertical riser to the second level at Line 3.

Piping System Description: System Configuration



Piping Run "C": a 4-inch-diameter pipe, which turns 90 degrees to parallel Line 3 at Column Line A-3.

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ASCE/SEI 7-22 Parameters and Coefficients

Coefficients for Mechanical and Electrical components (Table 13.6-1)

- Distribution systems – Piping and tubing not in accordance with ASME B31, including in-line components, constructed of high- or limited-deformability materials, with joints made by threading, bonding, compression couplings, or grooved couplings:
  - $C_{AR} = 2.2$
  - $R_{po} = 2.0$
  - $\Omega_{0p} = 1.75$
- Distribution system supports – hot-rolled steel bracing:
  - $C_{AR} = 1.0$
  - $R_{po} = 1.5$
  - $\Omega_{0p} = 2.0$

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ASCE/SEI 7-22 Parameters and Coefficients

- Design coefficients and factors for seismic force-resisting system (Table 12.2-1)
  Bearing frame system – steel BRBF: $R = 8.0$ and $\Omega_0 = 2.5$
- Short period design spectral acceleration, $S_{DS} = 1.00$
- Seismic Importance Factor, $I_e = 1.5$
- Component Importance Factor, $I_p = 1.5$
- Redundancy factor, $\rho = 1.0$
- Height of attachment at roof, $z = 30 \text{ ft}$
- Average roof height, $h = 30 \text{ ft}$
- Story height, $h_{sx} = 15 \text{ ft}$

Piping and Braces Parameters

- Gravity (non-seismic) support spacing, $L_{grav\ sup} = 10 \text{ ft}$
- Lateral brace spacing, $L_{lat\ brace} = 40 \text{ ft}$
- Longitudinal brace spacing, $L_{long\ brace} = 80 \text{ ft}$
- Length from Support 1 to mechanical unit, $L_{1M} = 9 \text{ ft}$
- ASTM A53 pipe with threaded connections, $F_y = 35{,}000 \text{ psi}$
- System working pressure, $P = 200 \text{ psi}$
- 4-inch diameter water-filled pipe weight, $D = W_p = 16.4 \text{ plf}$
- 6-inch diameter water-filled pipe weight, $D = W_p = 31.7 \text{ plf}$

ASCE/SEI 7-22 Parameters and Coefficients

- Approximate fundamental period of the supporting structure, T_a (Section 12.8.2.1)
  $T_a = C_t {h_n}^x = (0.03)(30 \text{ ft})^{0.75} = 0.38 \text{ s}$
- Force amplification factor as a function of height in the structure, H_f
  $a_1 = \frac{1}{T_a} = \frac{1}{0.38\, s} = 2.63 > 2.5$, use $a_1 = 2.5$
  $a_2 = [1 - (0.4/T_a)^2] = [1 - (0.4/0.38 \text{ s})^2] = -0.11 < 0$, use $a_2 = 0$
  $H_f = 1 + a_1\left(\frac{z}{h}\right) + a_2\left(\frac{z}{h}\right)^{10} = 1 + 2.5\left(\frac{30 \text{ ft}}{30 \text{ ft}}\right) + 0\left(\frac{30 \text{ ft}}{30 \text{ ft}}\right)^{10} = 3.5$
  For supporting structures with $T_a \leq 0.4$ s, $a_1 = 2.5$ and $a_2 = 0$.
- Structure ductility reduction factor, R_μ
  $R_\mu = (1.1\, R/(\, I_e\Omega_0))^{1/2} = (1.1(8/((1.5)(2.5)))^{1/2} = 1.53 \geq 1.3$

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Applicable Requirements

- Component failure shall not cause failure of an essential architectural, mechanical, or electrical component (Section 13.2.4).
- Seismic attachments shall be bolted, welded, or otherwise positively fastened without considering the frictional resistance produced by the effects of gravity (Section 13.4).
- F_p shall be applied at the component's center of gravity and distributed relative to the component's mass distribution (Section 13.3.1).
- Effects of seismic relative displacements shall be considered in combination with displacements caused by other loads as appropriate (Section 13.3.2) .
- Piping system shall be designed for the seismic forces and D_{pI} (Section 13.6.7).
- Distribution system supports shall be designed for seismic forces and D_{pI}. Distribution systems braced to resist vertical, transverse, and long. seismic loads (Section 13.6.7).

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Prescribed Seismic Forces: Piping System Design

- Seismic design force, F_p

$$F_p = 0.4S_{DS}I_pW_p\left[\frac{H_f}{R_\mu}\right]\left[\frac{C_{AR}}{R_{po}}\right] = 0.4(1.0)(1.5)(W_p)\left[\frac{3.5}{1.53}\right]\left[\frac{2.2}{2.0}\right] = 1.508W_p \quad \text{(controlling equation)}$$

$$F_{p,max} = 1.6S_{DS}I_pW_p = 1.6(1.0)(1.5)(W_p) = 2.40W_p$$

$$F_{p,min} = 0.3S_{DS}I_pW_p = 3(1.0)(1.5)(W_p) = 0.45W_p$$

- Horizontal seismic load effect, E_h

$$E_h = \rho Q_E = \rho F_p = (1.0)(1{,}072\text{ lb}) = 1{,}072\text{ lb}$$

- Vertical seismic load effect, E_v

$$E_v = 0.2S_{DS}D = (0.2)(0.474\text{g})(3{,}000\text{ lb}) = 284\text{ lb}$$

- Basic Load Combinations for Strength Design:

$1.2D + E_v + E_h + L + 0.2S$ (Load Combination 6) and $0.9D - E_v + E_h$ (Load Combination 7)

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Proportioning and Design: Piping System Design

4-in. diameter pipe (Pipe Runs "A" and "C")

- Inner diameter, $d_1 = 4.026$ in.
- Outer diameter, $d = 4.5$ in.
- Wall thickness, $t = 0.237$ in.
- Plastic modulus, $Z = 4.31$ in.^{3}
- Moment of inertia, $I = 7.23$ in.^{4}

6-in. diameter pipe (Pipe Run "B")

- Inner diameter, $d_1 = 6.065$ in.
- Outer diameter, $d = 6.625$ in.
- Wall thickness, $t = 0.28$ in.
- Plastic modulus, $Z = 11.28$ in.^{3}
- Moment of inertia, $I = 28.14$ in.^{4}

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Proportioning and Design: Piping System Design

Gravity and Pressure Loads

- Longitudinal stresses in piping due to pressure and weight

$f_L = \frac{Pd}{4t} + \frac{M_g}{Z}$, where $M_g = \frac{(D)\left(L_{grav\,sup}\right)^2}{8}$ is the resultant moment due to forces in gravity direction

For 4-inch-diameter pipe

$$M_g = \frac{(16.4\text{ plf})(10\text{ ft})^2}{8} = 2{,}460\text{ lb}-\text{in.}$$

$$f_{L,Dead} = \frac{M_g}{Z} = \frac{2{,}460\text{ lb}-\text{in.}}{4.31\text{ in.}^3} = 571\text{ psi}$$

$$f_{L,Pressure} = \frac{Pd}{4t} = \frac{(200\text{ psi})(4.5\text{ in.})}{4(0.237\text{ in.})} = 949\text{ psi}$$

For 6-inch-diameter pipe

$$M_g = \frac{(31.7\text{ plf})(10\text{ ft})^2}{8} = 4{,}755\text{ lb}-\text{in.}$$

$$f_{L,Dead} = \frac{M_g}{Z} = \frac{4{,}755\text{ lb}-\text{in.}}{11.28\text{ in.}^3} = 422\text{ psi}$$

$$f_{L,Pressure} = \frac{Pd}{4t} = \frac{(200\text{ psi})(6.625\text{ in.})}{4(0.28\text{ in.})} = 1{,}183\text{ psi}$$

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Proportioning and Design: Piping System Design

Seismic Loads on Piping Runs “A” and “C” – 4-in-diameter pipe

- Horizontal seismic load effect, $E_{h,}$ and vertical seismic load effect, E_v

$$F_p = 1.508W_p = 1.508(16.4\text{ plf}) = 24.7\text{ lb/ft}$$

$$E_h = \rho Q_E = \rho F_p = (1.0)(24.7\text{ lb/ft}) = 24.7\text{ lb/ft}$$

$$E_v = 0.2S_{DS}D = 0.2(1.0)(16.4\text{ plf}) = 3.28\text{ lb/ft}$$

- Maximum moment due to horizontal seismic load, M_{Eh}, and associated flexural stress

$$M_{Eh} = \frac{(E_h)(L_{lat\,brace})^2}{8} = \frac{(24.7\text{ lb/ft})(40\text{ ft})^2}{8} = 4{,}946\text{ lb}-\text{ft} = 59{,}353\text{ lb}-\text{in.}$$

$$f_{bh} = \frac{M_{Eh}}{Z} = \frac{59{,}353\text{ lb}-\text{in.}}{4.31\text{ in.}^3} = 13{,}766\text{ psi}$$

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Proportioning and Design: Piping System Design

Seismic Loads on Piping Runs "A" and "C" – 4-in-diameter pipe (Continued)

- Maximum moment due to vertical seismic load, M_{Ev}, and associated flexural stress

$$M_{Ev} = \frac{(E_v)(L_{grav\,sup})^2}{8} = \frac{(3.28\text{ plf})(10\text{ ft})^2}{8} = 41\text{ lb-ft} = 492\text{ lb-in.}$$

$$f_{bv} = \frac{M_{Ev}}{Z} = \frac{492\text{lb-in.}}{4.31\text{in.}^3} = 114\text{ psi}$$

- Design stress in the pipe, f_u, using Load Combination 6: $1.2D + E_v + E_h + L + 0.2S$

$$f_u = 1.2(f_{L,Dead} + f_{L,Pressure}) + f_{bv} + f_{bh}$$

$$f_u = 1.2(571\text{ psi} + 949\text{ psi}) + 114\text{ psi} + 13{,}766\text{ psi} = 15{,}704\text{ psi}$$

- Permissible stress check, $f_u < 0.7F_y$, where $0.7F_y = 0.7 \times 35{,}000\text{ psi} = 24{,}500\text{ psi}$

$15{,}704\text{ psi} < 24{,}500\text{ psi}$ OK

Proportioning and Design: Piping System Design

Seismic Loads on Piping Runs "B" – 6-in-diameter pipe

- Horizontal seismic load effect, E_h, and vertical seismic load effect, E_v

$$F_p = 1.508W_p = 1.508(31.7\text{ plf}) = 47.8\text{ lb/ft}$$

$$E_h = \rho Q_E = \rho F_p = (1)(47.8\text{ lb/ft}) = 47.8\text{ lb/ft}$$

$$E_v = 0.2S_{DS}D = 0.2(1.0)(31.7\text{ plf}) = 6.34\text{ lb/ft}$$

- Maximum moment due to horizontal seismic load, M_{Eh}, and associated flexural stress

$$M_{Eh} = \frac{(E_h)(L_{lat\,brace})^2}{8} = \frac{(47.8\text{ lb/ft})(40\text{ ft})^2}{8} = 9{,}560\text{ lb-ft} = 114{,}725\text{ lb-in.}$$

$$f_{bh} = \frac{M_{Eh}}{Z} = \frac{114{,}725\text{ lb-in.}}{11.28\text{ in.}^3} = 10{,}171\text{ psi}$$

Proportioning and Design: Piping System Design

Seismic Loads on Piping Runs "B" – 6-in-diameter pipe (Continued)

- Maximum moment due to vertical seismic load, M_{Ev}, and associated flexural stress

$$M_{Ev} = \frac{(E_v)(L_{grav\ sup})^2}{8} = \frac{(6.34 \text{ plf})(10 \text{ ft})^2}{8} = 79 \text{ lb–ft} = 951 \text{ lb–in.}$$

$$f_{bv} = \frac{M_{Ev}}{Z} = \frac{951 \text{ lb–in.}}{11.28 \text{ in.}^3} = 84 \text{ psi}$$

- Design stress in the pipe, f_u, using Load Combination 6: $1.2D + E_v + E_h + L + 0.2S$

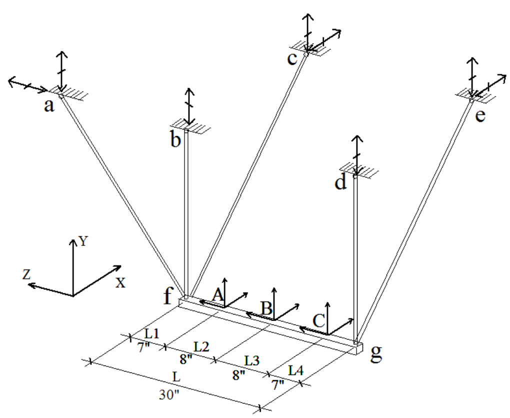
$$f_u = 1.2(f_{L,Dead} + f_{L,Pressure}) + f_{bv} + f_{bh}$$

$$f_u = 1.2(421 \text{ psi} + 1{,}183 \text{ psi}) + 84 \text{ psi} + 10{,}171 \text{ psi} = 12{,}181 \text{ psi}$$

- Permissible stress check, $f_u < 0.7F_y$, where $0.7F_y = 0.7 \times 35{,}000 \text{ psi} = 24{,}500 \text{ psi}$

$12{,}181 \text{ psi} < 24{,}500 \text{ psi}$ OK

Prescribed Seismic Forces: Pipe Supports and Bracing



Design demands on piping support assembly

- Design demands are calculated for vertical supports, lateral supports, and anchorage at Support 1.
- The following elements should be designed:
  - Beam f-g
  - Hangers f-b and g-d
  - Transvers brace a-f
  - Longitudinal braces f-c and g-e
  - Connections at a, b, c, d, and e

Prescribed Seismic Forces: Pipe Supports and Bracing

- Seismic design force, F_p

  $F_p = 0.4 S_{DS} I_p W_p \left[\frac{H_f}{R_\mu}\right] \left[\frac{C_{AR}}{R_{po}}\right] = 0.4(1.0)(1.5)(W_p) \left[\frac{3.5}{1.53}\right] \left[\frac{1.0}{1.5}\right] = 0.914 W_p$ (controlling equation)

  $F_{p,max} = 1.6 S_{DS} I_p W_p = 1.6(1.0)(1.5)(W_p) = 2.40 W_p$

  $F_{p,min} = 0.3 S_{DS} I_p W_p = 3(1.0)(1.5)(W_p) = 0.45 W_p$

- Horizontal seismic load effect, E_h

  $E_h = \rho Q_E = \rho F_p = (1.0)(0.914 W_p) = 0.914 W_p$

- Vertical seismic load effect, E_v

  $E_v = 0.2 S_{DS} D$

- Basic Load Combinations for Strength Design:

  $1.2D + E_v + E_h + L + 0.2S$ (Load Combination 6) and $0.9D - E_v + E_h$ (Load Combination 7)

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Proportioning and Design: Pipe Supports and Bracing

Vertical Loads

- For 4-inch diameter pipes

  Dead load, $P_{v4} = (D)(L_{grav\ sup}) = (16.4\ \text{plf})(10\ \text{ft}) = 164\ \text{lb}$

  Vertical seismic load, $P_{Ev4} = 0.2 S_{DS} D (L_{grav\ sup}) = 0.2(1.0)(16.4\ \text{plf})(10\ \text{ft}) = 33\ \text{lb}$

- For 4-inch diameter pipes

  Dead load, $P_{v6} = (D)(L_{grav\ sup}) = (31.7\ \text{plf})(10\ \text{ft}) = 317\ \text{lb}$

  Vertical seismic load, $P_{Ev6} = 0.2 S_{DS} D (L_{grav\ sup}) = 0.2(1.0)(31.7\ \text{plf})(10\ \text{ft}) = 63\ \text{lb}$

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Proportioning and Design: Pipe Supports and Bracing

Longitudinal Lateral Loads

- For Piping Run "A", the total length of pipe tributary to Support 1 is 40 feet (half the distance between longitudinal braces at Supports 1 and 3) plus 9 feet (length of pipe from Support 1 to Support M, the mechanical unit), or 49 feet:

  $$P_{X1A} = \rho F_p = \rho(0.914W_p) = (1)(0.914)(16.4\ \text{lb/ft})(49\ \text{ft}) = 734\ \text{lb}$$

- For Piping Runs "B" and "C", the total length of pipe tributary to Support 1 is approximately 80 feet:

  $$P_{X1B} = \rho F_p = \rho(0.914W_p) = (1)(0.914)(31.7\ \text{lb/ft})(80\ \text{ft}) = 2{,}318\ \text{lb}$$

  $$P_{X1C} = \rho F_p = \rho(0.914W_p) = (1)(0.914)(16.4\ \text{lb/ft})(80\ \text{ft}) = 1{,}199\ \text{lb}$$

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Proportioning and Design: Pipe Supports and Bracing

Transverse Lateral Loads

- Pipes are idealized as continuous beams spanning between pinned connections, representing the transverse braces. Reaction at the beam's midspan is calculated as:

  $$P_Z = \frac{5}{8}\, W(L_{left} + L_{right})$$

- For Piping Run "A", we analyze the transverse Support 1, which is adjacent to the mechanical unit. The total length between the support and the unit is $L_{1M} = 9$ ft

  $$P_{Z1A} = \left(\frac{5}{8}\right) W(L_{left} + L_{right}) = \left(\frac{5}{8}\right) (\rho F_p)(L_{1M} + L_{lat\ brace})$$

  $$P_{Z1A} = \left(\frac{5}{8}\right) (1)(0.914)\left(16.4\frac{\text{lb}}{\text{ft}}\right)(9\ \text{ft} + 40\ \text{ft}) = 459\ \text{lb}$$

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Proportioning and Design: Pipe Supports and Bracing

Transverse Lateral Loads (Continued)

- For Piping Runs "B" and "C", we assume that 5/8 of the total length of pipe on each side of Support 1 is laterally braced at Support 1

$$P_{Z1B} = \left(\frac{5}{8}\right) W(L_{left} + L_{right}) = \left(\frac{5}{8}\right) (\rho F_p)((2)(L_{lat\,brace}))$$

$$P_{Z1B} = \left(\frac{5}{8}\right) (1)(0.914) \left(31.7 \frac{\text{lb}}{\text{ft}}\right) ((2)(40\text{ ft})) = 1{,}449\text{ lb}$$

$$P_{Z1C} = \left(\frac{5}{8}\right) W(L_{left} + L_{right}) = \left(\frac{5}{8}\right) (\rho F_p)((2)(L_{lat\,brace}))$$

$$P_{Z1C} = \left(\frac{5}{8}\right) (1)(0.914) \left(16.4 \frac{\text{lb}}{\text{ft}}\right) ((2)(40\text{ ft})) = 749\text{ lb}$$

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Prescribed Seismic Displacements

Design for Displacements within Structures

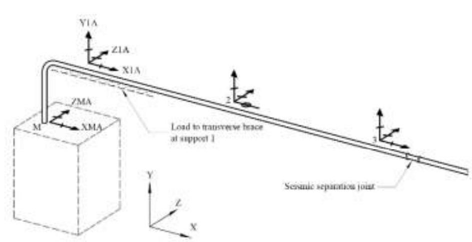
- The building is designed for a maximum allowable story drift of 1.5% per floor.

  Allowable story drift, $\Delta_a = 0.015 h_{sx} = 0.015(15\text{ ft})(12\text{ in./ft}) = 2.7\text{ in.}$

- Seismic relative displacements, D_{pI}

  $D_{pI} = D_p I_e = (2.7\text{ in.})(1.5) = 4.05\text{ in.}$

- Drift can be accommodated by providing a flexible coupling or through bending in the pipe.
- Piping Run "A" connects to a large mechanical unit at Line 1 supported at Level 2. The entire story drift must be accommodated in the 5 feet piping drop.



Pipe run "A" - 4-inch dia.

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Prescribed Seismic Displacements

Design for Displacements within Structures (Continued)

- For a 4-inch-diameter pipe, assuming the pipe is fixed against rotation at both ends, the shear and moments required to deflect the pipe 4.05 in. are:

$$V = \frac{12EID_{pI}}{L^3} = \frac{12(29{,}000{,}000\text{ psi})(7.23\text{ in.}^4)(4.05\text{ in.})}{((5\text{ ft})(12\text{ in./ft}))^3} = 47{,}193\text{ lb}$$

$$M = VL = (47{,}176\text{ lb})(5\text{ ft})(12\text{ in./ft}) = 2{,}831{,}563\text{ lb–in.}$$

- The stress in the pipe displaced D_{pI} is:

$$f_b = \frac{M}{Z} = \frac{2{,}831{,}563\text{ lb–in.}}{4.31\text{ in.}^3} = 656{,}750\text{ psi}$$

- The permissible stress is $0.7F_y = 0.7(35{,}000\text{ psi}) = 24{,}500\text{ psi.}$
- The demand far exceeds the capacity of the pipe. Therefore, either a flexible coupling or a loop piping layout is required to accommodate the story drift.

Prescribed Seismic Displacements

Design for Displacements within Structures (Continued)

- Piping Run "B" drops from the roof to Level 2 at Line 3. The drift is the same and it can be accommodated over the full story height of 15 feet.

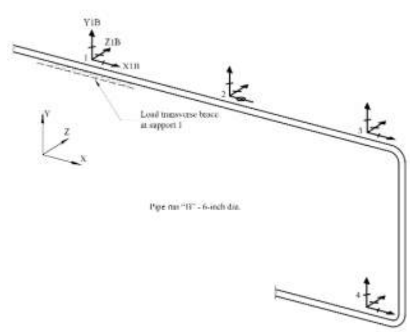
$$V = \frac{12EID_{pI}}{L^3} = \frac{12(29{,}000{,}000\text{ psi})(28.14\text{ in.}^4)(4.05\text{ in.})}{((15\text{ ft})(12\text{ in./ft}))^3} = 6{,}801\text{ lb}$$

$$M = VL = (6{,}800\text{ lb})(15\text{ ft})(12\text{ in./ft})/2 = 612{,}092\text{ lb–in.}$$

- The stress in the pipe displaced D_{pI} is:

$$f_b = \frac{M}{Z} = \frac{612{,}092\text{ lb–in.}}{11.28\text{ in.}^3} = 54{,}264\text{ psi}$$

- The permissible stress is $0.7F_y = 0.7(35{,}000\text{ psi}) = 24{,}500\text{ psi.}$
- The demand exceeds the permissible stress in the pipe, but not by a wide margin.



Prescribed Seismic Displacements

Design for Displacements Between Structures

- At the roof, Piping Run "A" crosses a seismic separation between adjacent two-story structures. The story heights are 15 ft and buildings are designed for $\Delta_a = 0.015h_{sx}$.

  Deflections of the buildings:

  $$\delta_{XA} = \delta_{XB} = (2)0.015h_{sx} = (2)(0.015)(15\text{ ft})(12\text{ in./ft}) = 5.4\text{ in.}$$

  Displacement demand:

  $$D_{pmax} = |\delta_{XA}| + |\delta_{XB}| = |5.4\text{ in.}| + |5.4\text{ in.}| = 10.8\text{ in.}$$

  Seismic relative displacements:

  $$D_{pI} = D_p I_e = (10.8\text{ in.})(1.5) = 16.2\text{ in.}$$

- The seismic separation joint must accommodate movement perpendicular and parallel to the pipe. Assuming an 18-inch joint, the joint could vary from 8.1 in. to 32.4 in.

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Questions?

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Elevated Vessel Seismic Design

- Vessel support and attachments
- Supporting frame

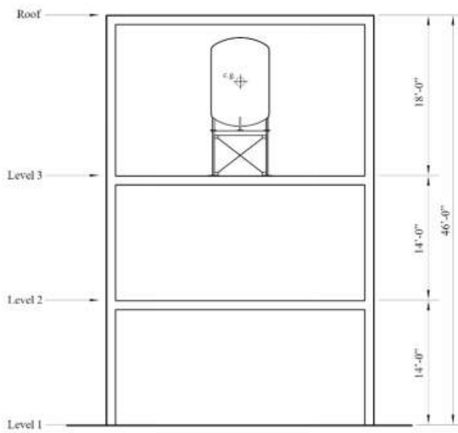
Elevated Vessel Description

Example Summary

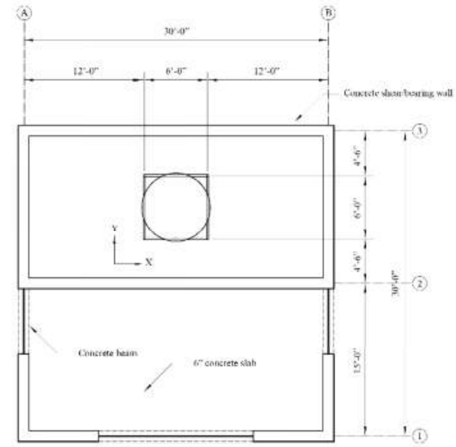
- **Nonstructural components:** Mechanical and electrical – pressure vessel not supported on skirts
- **Building seismic force-resisting system:** Special reinforced concrete shear walls
- **Equipment support:** Equipment support structures and platforms – Seismic Force-Resisting Systems with $R > 3$
- **Occupancy:** Storage
- **Risk Category:** II
- **Component Importance Factor:** $I_p = 1.0$
- **Number of stories:** 3
- $S_{DS} = 1.20$
- $S_1 = 0.65$

- Vessel supported by an OCBF platform with tension-only rods as braces.
- The vessel contains a non-hazardous compressed non-flammable gas.
- The weight of the vessel is less than 5% the total weight of the building structure, which is below the 20% threshold where ASCE/SEI 7-22 requires it be designed as a nonbuilding structure per Chapter 15.

Elevated Vessel Description



Elevated vessel – section



Elevated vessel – Level 3 plan

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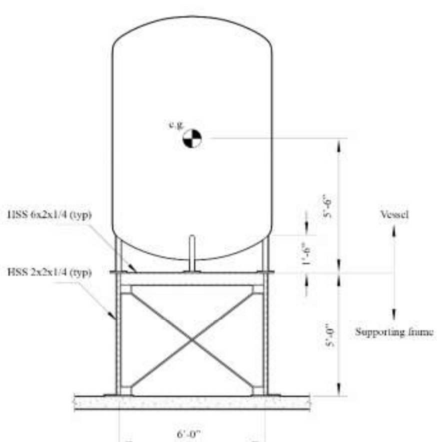
ASCE/SEI 7-22 Parameters and Coefficients



Changes in ASCE/SEI 7-22

ASCE/SEI 7-16 required the nonstructural components and supporting structure to be designed with the same seismic design forces, F_p, regardless of their interaction, and the force was based on the component properties. A platform supporting a pressure vessel would be designed for pressure vessel forces regardless of whether the platform structure was made of concrete, steel braced frames, or steel moment frames.

In ASCE/SEI 7-22, the concept of an equipment support structure or platform has been introduced and defined. Definitions are given in Section 11.2 and properties have been added to Table 13.6-1. Section 13.6.4.6 has been added to ASCE/SEI 7-22 to require that the support structures and platforms be designed in accordance with those properties. This permits a more accurate determination of forces that more realistically reflect the differences in dynamic properties and ductilities between the component and the support structure or platform.

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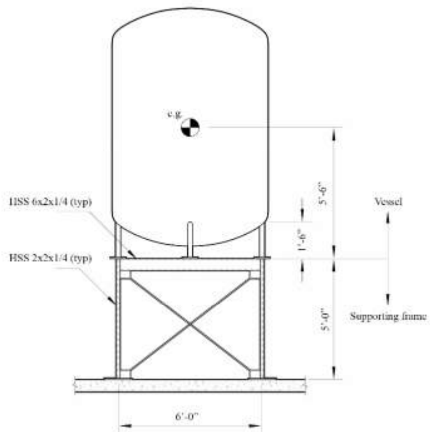
Elevated Vessel Description



Elevated vessel – supporting frame system

- Section 13.6.4.6 requires the engineers to select the seismic force-resisting system listed in Chapter 12 or Chapter 15 for equipment support structures and platforms.
- C_{AR} for the supported component cannot be less than that for the equipment support structure.
- The reactions applied by the component to the support structure can either stay the same or are effectively scaled down using a two-stage analysis approach.

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ASCE/SEI 7-22 Parameters and Coefficients

Coefficients for Mechanical and Electrical Components (Table 13.6-1)

- Mechanical and electrical components – Engines, turbines, pumps, compressors, and pressure vessels not supported on skirts and not within the scope of Chapter 15:
  - $C_{AR} = \cancel{1.0}\quad 1.4$
  - $R_{po} = 1.5$
  - $\Omega_{0p} = 2.0$

New concept: Per Section 13.3.1.3, C_{AR} for the vessel shall not be less than C_{AR} used for equipment support structure or platform itself.

- Equipment support structures and platforms – Seismic Force-Resisting Systems with R>3 (Building frame system – steel ordinary concentrically braced frame, *R*=6 per Table 12.2-1):
  - $C_{AR} = 1.4$
  - $R_{po} = 1.5$
  - $\Omega_{0p} = 2.0$

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ASCE/SEI 7-22 Parameters and Coefficients

- Design coefficients and factors for seismic force-resisting system (Table 12.2-1)
  Bearing wall system – special reinforced concrete shear walls: $R = 5.0$ and $\Omega_0 = 2.5$
- Short period design spectral acceleration, $S_{DS} = 1.20$
- Seismic Importance Factor, $I_e = 1.0$
- Component Importance Factor, $I_p = 1.0$
- Redundancy factor, $\rho = 1.0$
- Height of attachment at roof, $z = 28\text{ ft}$
- Average roof height, $h = 46\text{ ft}$

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ASCE/SEI 7-22 Parameters and Steel Material Properties

- Vessel and legs weight, $D_{ves} = W_{p,ves} = 5{,}000\text{ lb}$
- Supporting frame weight, $D_{sup} = W_{p,sup} = 1{,}000\text{ lb}$
- Vessel leg length, $L_{leg} = 18\text{ in.}$

Steel material properties

- HSS sections: ASTM A500 Grade B, $F_y = 46{,}000\text{ psi}$, $F_u = 58{,}000\text{ psi}$
- Bars and Plates: ASTM A36, $F_y = 36{,}000\text{ psi}$, $F_u = 58{,}000\text{ psi}$
- Pipes: ASTM A53 Grade B, $F_y = 35{,}000\text{ psi}$, $F_u = 60{,}000\text{ psi}$
- Bolts and threaded rods: ASTM A307

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ASCE/SEI 7-22 Parameters and Coefficients

- Approximate fundamental period of the supporting structure, T_a (Section 12.8.2.1)

  $T_a = C_t {h_n}^x = (0.02)(46 \text{ ft})^{0.75} = 0.353 \text{ s}$

- Force amplification factor as a function of height in the structure, H_f

  $a_1 = \frac{1}{T_a} = \frac{1}{0.353 \text{ s}} = 2.83 > 2.5$, use $a_1 = 2.5$

  $a_2 = [1 - (0.4/T_a)^2] = [1 - (0.4/0.353\ s)^2] = -0.28 < 0$, use $a_2 = 0$

  $H_f = 1 + a_1\left(\frac{z}{h}\right) + a_2\left(\frac{z}{h}\right)^{10} = 1 + 2.5\left(\frac{28 \text{ ft}}{46 \text{ ft}}\right) + 0\left(\frac{28 \text{ ft}}{46 \text{ ft}}\right)^{10} = 2.52$

  For supporting structures with $T_a \le 0.4$ s, $a_1 = 2.5$ and $a_2 = 0$.

- Structure ductility reduction factor, R_μ

  $R_\mu = (1.1\,R/(\,I_e\Omega_0))^{1/2} = (1.1(5/((1)(2.5)))^{1/2} = 1.48 \ge 1.3$

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Applicable Requirements

- Component failure shall not cause failure of an essential architectural, mechanical, or electrical component (Section 13.2.4).
- Seismic attachments shall be bolted, welded, or otherwise positively fastened without considering the frictional resistance produced by the effects of gravity (Section 13.4).
- F_p shall be applied at the component's center of gravity and distributed relative to the component's mass distribution (Section 13.3.1).
- Effects of seismic relative displacements shall be considered in combination with displacements caused by other loads as appropriate (Section 13.3.2).
- Local elements of the structure, including connections, shall be designed and constructed for the component forces where they control the design of the elements or their connections (Section 13.4).

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Applicable Requirements (Continued)

- Attachments to concrete or masonry shall be designed to resist the seismic load effects including overstrength; Ω_0 shall be taken as Ω_{0p} (Section 13.4.2).
- The equipment support structures and platforms shall be designed for F_p. The seismic force-resisting system for the equipment support structures and platforms shall conform to one of the types indicated in Table 12.2-1 or Table 15.4-1 and abide by the system limitations noted in the tables (Section 13.6.4.6).

Prescribed Seismic Forces: Vessel Support and Attachments

- Vessel and legs weight, $W_{p,ves} = D_{ves} = 5{,}000 \text{ lb}$
- Seismic design force, F_p

$$F_p = 0.4 S_{DS} I_p W_p \left[\frac{H_f}{R_\mu}\right]\left[\frac{C_{AR}}{R_{po}}\right] = 0.4(1.2)(1.0)(W_p)\left[\frac{2.52}{1.48}\right]\left[\frac{1.4}{1.5}\right] = 0.762 W_p \quad \text{(controlling equation)}$$

$$F_{p,max} = 1.6 S_{DS} I_p W_p = 1.6(1.2)(1.0)(W_p) = 1.92 W_p$$

$$F_{p,min} = 0.3 S_{DS} I_p W_p = 0.3(1.2)(1.0)(W_p) = 0.360 W_p$$

$$F_{p,ves} = 0.762 W_p = 0.762(5{,}000 \text{ lb}) = 3{,}808 \text{ lb} \quad \text{(controlling seismic design force)}$$

Prescribed Seismic Forces: Vessel Support and Attachments

- Horizontal seismic load effect, E_h

  $Q_E = F_p = 3{,}808 \text{ lb}$

  $E_{h,ves} = \rho Q_E = (1.0)(3{,}808 \text{ lb}) = 3{,}808 \text{ lb}$

- Vertical seismic load effect, E_v

  $E_{v,ves} = 0.2 S_{DS} D = (0.2)(1.2\text{g})(5{,}000 \text{ lb}) = 1{,}200 \text{ lb}$

- Basic Load Combinations for Strength Design to determine the design member and connection forces to be used in conjunction with seismic loads:

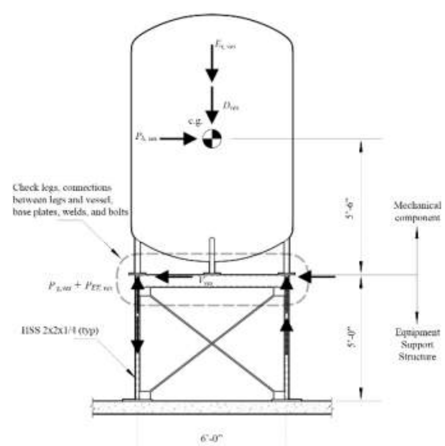
  $1.2D + E_v + E_h + L + 0.2S$ (Load Combination 6)

  $0.9D - E_v + E_h$ (Load Combination 7)

  For nonstructural components, the terms *L* and *S* are typically zero.

Proportioning and Design: Vessel Support and Attachments

- Components to be designed
  - Legs supporting the vessel
  - Connection between the legs and vessel shell
  - Base plates and welds attaching them to legs
  - Bolts connecting base plates to supporting frame



Free body diagram for vessel support and attachments design

Proportioning and Design: Vessel Support and Attachments

- Vessel vertical load in each leg due to dead load, $P_{g,ves}$

$$P_{g,ves} = \frac{D_{ves}}{4 \text{ legs}} = \frac{5{,}000 \text{ lb}}{4 \text{ legs}} = 1{,}250 \text{ lb/leg}$$

- Vessel vertical load in each leg due to vertical seismic load effect, $P_{Ev,ves}$

$$P_{Ev,ves} = \frac{E_{v,ves}}{4 \text{ legs}} = \frac{1{,}200 \text{ lb}}{4 \text{ legs}} = 300 \text{ lb/leg}$$

- Vessel shear force in each leg due to the horizontal seismic load effect, V_{ves}

$$V_{ves} = \frac{E_{h,ves}}{4 \text{ legs}} = \frac{3{,}808 \text{ lb}}{4 \text{ legs}} = 952 \text{ lb/leg}$$

- Overturning moment at the bottom of leg base plates, height of 5.5 feet

$$M = (5.5 \text{ ft})(E_{h,ves}) = (5.5 \text{ ft})(3{,}808 \text{ lb}) = 20{,}946 \text{ lb–ft}$$

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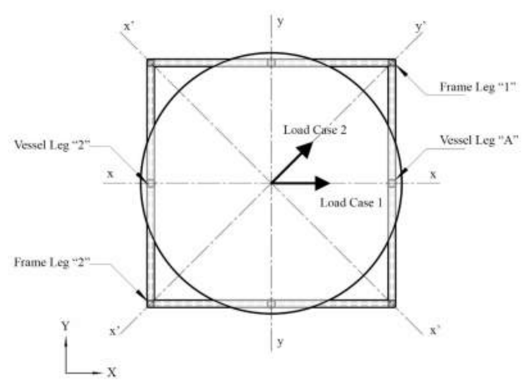
Proportioning and Design: Vessel Support and Attachments

- F_p shall be applied independently in at least two orthogonal horizontal directions.
- For vertically cantilevered systems, the lateral force also shall be assumed to act in any horizontal direction.
- In this example, the layout of the vessel legs is symmetric, and there are two horizontal directions of interest, separated by 45 degrees.



Elevated vessel support load cases

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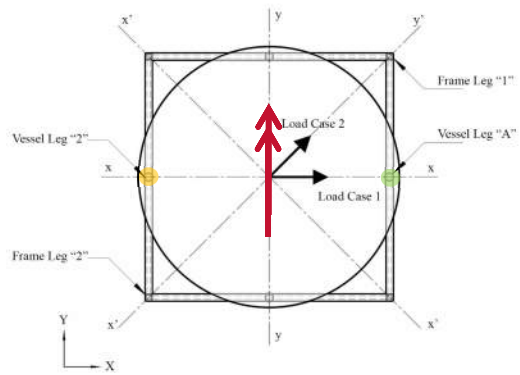
Proportioning and Design: Vessel Support and Attachments

Load Case 1 – Overturning moment about y-y axis

- Overturning moment is resisted by two legs along the x-x axis (one in tension and other in compression). The vessel rotates about the legs on the y-y axis.
- Maximum tension and compression loads in each leg, where the distance between Legs A and C is $d = 6$ ft:

$$P_{Eh_{y-y}} = \frac{M}{d} = \frac{20{,}946\ \text{lb-ft}}{6\ \text{ft}} = 3{,}491\ \text{lb}$$



Elevated vessel support load cases

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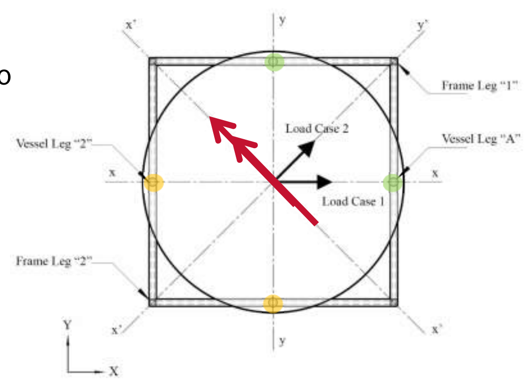
Proportioning and Design: Vessel Support and Attachments

Load Case 2 – Overturning moment about x'-x' axis

- Overturning moment is resisted by four legs (two in tension and two in compression). The vessel rotates about the legs on the x'-x' axis.
- Maximum tension and compression loads in each leg, where the distance between Legs A and C is $d/\sqrt{2}$=4.24 ft:

$$P_{Eh_{x'-x'}} = \frac{M}{2(d/\sqrt{2})} = \frac{20{,}946\ \text{lb-ft}}{2(4.24\ \text{ft})} = 2{,}469\ \text{lb}$$



Elevated vessel support load cases

Load Case 1 governs the vessel leg design

$$P_{Eh,ves} = P_{Eh_{y-y}} = 3{,}491\ \text{lb}$$

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Proportioning and Design: Vessel Support and Attachments

- The design compression loads on the vessel legs is controlled by Load Combination 6:

  $1.2D + E_v + E_h + L + 0.2S$

  $C_u = 1.2(P_{g,ves}) + P_{Ev,ves} + P_{Eh,ves} = 1.2(1{,}250\text{ lb}) + 300\text{ lb} + 3{,}491\text{ lb} = 5{,}291\text{ lb}$
- The design tension load on the vessel legs is controlled by Load Combination 7:

  $0.9D - E_v + E_h$

  $T_u = 0.9(P_{g,ves}) - P_{Ev,ves} + P_{Eh,ves} = 0.9(1{,}250\text{ lb}) - 300\text{ lb} - 3{,}491\text{ lb} = -2{,}666\text{ lb}$ (tension)
- The vessel legs shall be designed for the following shear force:

  $V_u = V_{ves} = 952\text{ lb}$

Proportioning and Design: Vessel Support and Attachments

Vessel Leg Design

- Section properties of the vessel leg: $A = 1.02\text{ in.}^2$ and $Z = 0.713\text{ in.}^3$
- Maximum axial compressive stress in the leg:

  $f_a = \frac{C_u}{A} = \frac{5{,}291\text{ lb}}{1.02\text{ in.}^2} = 5{,}291\text{ psi}$
- Moment and bending stress in the leg, assuming pinned-fixed condition at connections:

  $M_u = (V_u)(L_{leg}) = (952\text{ lb})(18\text{ in.}) = 17{,}138\text{ lb}-\text{in.}$

  $f_b = \frac{M_u}{Z} = \frac{17{,}138\text{ lb}-\text{in.}}{0.713\text{ in.}^3} = 24{,}036\text{ psi}$
- Permissible compressive strength, and bending strength: $F_a = F_{bw} = 31{,}500\text{ psi}$
- Combined loading:

  $\left|\frac{f_a}{F_a} + \frac{f_b}{F_{bw}}\right| = \left|\frac{5{,}291\text{ psi}}{31{,}500\text{ psi}} + \frac{24{,}036\text{ psi}}{31{,}500\text{ psi}}\right| = 0.93 \le 1.0$ →OK

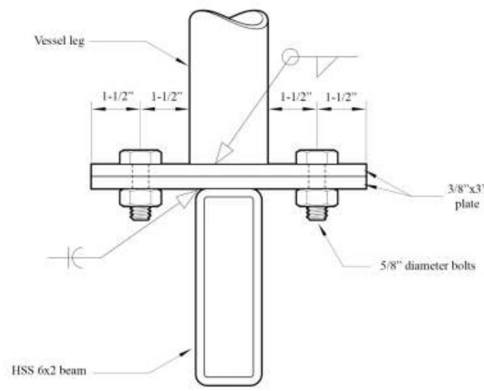
Proportioning and Design: Vessel Support and Attachments

Connections of the Vessel Leg

- The design of this connection involves checking the
  - Weld between the pipe leg and the base plate
  - Base plate
  - Bolts to the supporting frame
- Maximum compression and tension:

  $C_u = 5{,}291$ lb and $T_u = -2{,}666$ lb (tension)
- Design shear in each leg:

  $V_u = 952$ lb



Elevated vessel leg connection

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Proportioning and Design: Vessel Support and Attachments

Connections of the Vessel Leg – Bolts

- Each vessel leg connection has two bolts, thus, the connection demand is divided by two
- Maximum tension in each bolt:

  $$T_{u,bolt} = \frac{T_u}{2\text{ bolts}} = \frac{-2{,}666\text{ lb}}{2\text{ bolts}} = -1{,}333\text{ lb/bolt}$$
- Maximum shear per bolt:

  $$V_{u,bolt} = \frac{V_u}{2\text{ bolts}} = \frac{952\text{ lb}}{2\text{ bolts}} = 476\text{ lb/bolt}$$
- Available tensile and shear strengths of the of 5/8-inch-diameter ASTM A307 bolts:

  $\phi r_n = 10{,}400$ lb (tension) and $\phi_v r_n = 5{,}520$ lb (shear)
- Bolts are adequate, $\phi r_n > T_{u,bolt}$ and $\phi_v r_n > V_{u,bolt}$ OK

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Proportioning and Design: Vessel Support and Attachments

Connections of the Vessel Leg – Connection Plates

- Connection plates are 3/8 inch thick and 3 inches wide. The plastic section modulus is:

$$Z = \frac{bd^2}{4} = \frac{(3\text{ in.})(0.375\text{ in.})^2}{4} = 0.1055\text{ in.}^3$$

- Maximum moment in the plate based on the 1.5 in. edge distance to the bolt centerline:

$$M_{u,plate} = T_{u,bolt}(1.5\text{ in.}) = (1{,}333\ \text{lb/bolt})(1.5\text{ in.}) = 1{,}999\text{ lb}-\text{in.}$$

- Bending stress in the plate:

$$f_b = \frac{M_u}{Z} = \frac{1{,}999\text{ lb}-\text{in.}}{0.1055\text{ in.}^3} = 18{,}958\text{ psi}$$

- Bending stress capacity of the ASTM A36 plate:

$$F_b = \Phi F_y = 0.9(36{,}000\text{ psi}) = 32{,}400\text{ psi}$$

- Steel plate is adequate, $F_b > f_b$ →OK

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Proportioning and Design: Vessel Support and Attachments

Connections of the Vessel Leg – Connection Plates (Continued)

- ANSI/AISC 360 Equation 9-20 permits prying action to be neglected if plates meets minimum thickness requirement:

$t_{min} = \sqrt{\frac{4.44Tb'}{pF_u}}$, where $p = 3$ in. is the tributary length per pair of bolts.

$$b' = (b - db/2) = (1.5\text{ in.} - 0.625\text{ in.}/2) = 1.188\text{ in.}$$

$$t_{min} = \sqrt{\frac{4.44Tb'}{pF_u}} = \sqrt{\frac{(4.44)(1{,}333\text{ lb/bolt})(1.188\text{ in.})}{(3\text{ in.})(58{,}000\text{ psi})}} = 0.201\text{ in.}$$

- $t_{\text{min}} = 0.201$ in. is less than the 0.375-inch thickness provided for the connection plates. Thus, prying action need not be considered further.

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Proportioning and Design: Vessel Support and Attachments

Connections of the Vessel Leg – Welds

- The vessel legs have two welds at each end: the welds to the vessel body, and the welds to the upper connection plate.
- The outer diameter of the vessel leg is $d = 2.38$ in. The weld properties are simplified by assuming a weld of unit thickness.

$$Z_w = \frac{\pi d^2}{4} = \frac{\pi(2.38\text{ in.})^2}{4} = 4.45\text{ in.}^2$$

$$A = \pi d = \pi(2.38\text{ in.}) = 7.48\text{ in.}$$

- Shear force in the weld of unit thickness:

$$v = \frac{V_u}{A} = \frac{952\text{ lb}}{7.48\text{ in.}} = 127\text{ lb/in.}$$

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Proportioning and Design: Vessel Support and Attachments

Connections of the Vessel Leg – Welds (Continued)

- Tension force due to axial load in a weld of unit thickness:

$$T_a = \frac{T_u}{A} = \frac{2{,}666\text{ lb}}{7.48\text{ in.}} = 356\text{ lb/in.}$$

- Tension force due to bending in a weld of unit thickness (at connection to the vessel):

$$T_b = \frac{M}{Z_w} = \frac{17{,}138\text{ lb}-\text{in.}}{4.45\text{ in.}^2} = 3{,}852\text{ lb/in.}$$

- For a unit length, a 3/16-inch fillet weld has a capacity of:

$$\phi R_n = 1.392\,DL = 1.392\,(3)(1) = 4.18\,\frac{\text{kip}}{\text{in.}}$$

- Thus, the 3/16-inch fillet weld is adequate.

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Prescribed Seismic Forces: Supporting Frame

- Supporting frame weight, $W_{p,sup} = D_{sup} = 1{,}000\text{ lb}$
- Seismic design force, F_p

$$F_p = 0.4S_{DS}I_pW_p\left[\frac{H_f}{R_\mu}\right]\left[\frac{C_{AR}}{R_{po}}\right] = 0.4(1.2)(1.0)(W_p)\left[\frac{2.52}{1.48}\right]\left[\frac{1.4}{1.5}\right] = 0.762W_p \quad \text{(controlling equation)}$$

$$F_{p,max} = 1.6S_{DS}I_pW_p = 1.6(1.2)(1.0)(W_p) = 1.92W_p$$

$$F_{p,min} = 0.3S_{DS}I_pW_p = 0.3(1.2)(1.0)(W_p) = 0.360W_p$$

$$F_{p,sup} = 0.762W_p = 0.762(1{,}000\text{ lb}) = 762\text{ lb} \quad \text{(controlling seismic design force)}$$

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Prescribed Seismic Forces: Supporting Frame

- Horizontal seismic load effect, E_h

$$Q_E = F_p = 762\text{ lb}$$

$$E_{h,sup} = \rho Q_E = (1.0)(762\text{ lb}) = 762\text{ lb}$$

- Vertical seismic load effect, E_v

$$E_{v,sup} = 0.2S_{DS}D = (0.2)(1.2\text{g})(1{,}000\text{ lb}) = 240\text{ lb}$$

- Basic Load Combinations for Strength Design to determine the design member and connection forces to be used in conjunction with seismic loads:

$$1.2D + E_v + E_h + L + 0.2S \quad \text{(Load Combination 6)}$$

$$0.9D - E_v + E_h \quad \text{(Load Combination 7)}$$

For nonstructural components, the terms *L* and *S* are typically zero.

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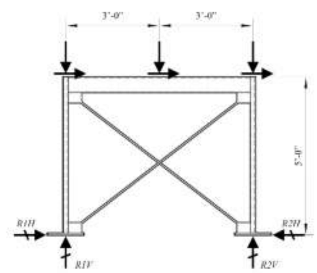
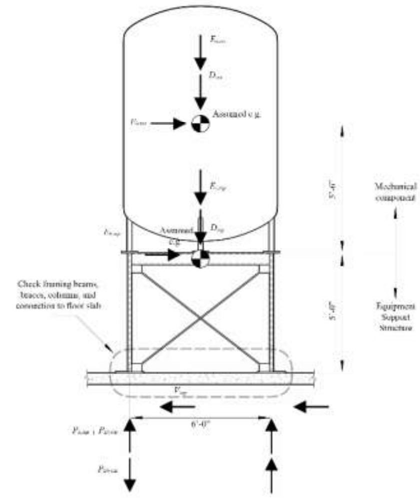
Proportioning and Design: Supporting Frame

- Components to be designed
  - Beams supporting the vessel legs
  - Braces
  - Columns supporting the platform and vessel
  - Base plates and anchor bolts



Elevated vessel supporting frame



Free body diagram for supporting frame system

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Proportioning and Design: Supporting Frame

Support Frame Beams

- Beam vertical load at midspan due to dead load, $P_{g,sup}$

$$P_{g,sup} = \frac{D_{ves}+D_{sup}}{4\text{ supports}} = \frac{5{,}000\text{ lb}+1{,}000\text{ lb}}{4\text{ supports}} = 1{,}500\text{ lb/support}$$

- Beam vertical load at midspan due to vertical seismic load effect, $P_{Ev,sup}$

$$P_{Ev,sup} = \frac{E_{v,ves}+E_{v,sup}}{4\text{ supports}} = \frac{1{,}200\text{ lb}+240\text{ lb}}{4\text{ supports}} = 360\text{ lb/support}$$

- Beam lateral load of the combined vessel and supporting frames, V_{sup}

$$V_{sup} = \frac{E_{h,ves}+E_{h,sup}}{4\text{ supports}} = \frac{3{,}808\text{ lb}+762\text{ lb}}{4\text{ supports}} = 1{,}143\text{ lb/support}$$

- Beam vertical load at midspan due to horizontal seismic load effect (Case 1), $P_{Eh,beam}$

$$P_{Eh,beam} = P_{Eh,ves} = 3{,}491\text{ lb/support}$$

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Proportioning and Design: Supporting Frame

Support Frame Beams (Continued)

- The HSS6x2x1/4 frame beams have the following geometric and material properties:

$$Z_{x-x} = 5.84\text{ in.}^3,\ Z_{y-y} = 2.61\text{ in.}^3,\ F_b = \Phi F_y = 0.9(46{,}000\text{ psi}) = 41{,}400\text{ psi}$$

- Moment and bending stress about the x-x axis in the beams, where $L = 6\ ft$

$$M_{x-x} = \frac{C_u L}{4} = \frac{(5{,}651\text{ lb})(6\text{ ft})(12\text{ in./ft})}{4} = 101{,}718\text{ lb−in.} \quad f_{bx} = \frac{M_{x-x}}{Z_{x-x}} = \frac{101{,}718\text{ lb −in.}}{5.84\text{ in.}^3} = 17{,}417\text{ psi}$$

- Moment and bending stress about the y-y axis in the beams, where $L = 6$ ft

$$M_{y-y} = \frac{V_u L}{4} = \frac{(1{,}143\text{ lb})(6\text{ ft})(12\text{ in./ft})}{4} = 20{,}565\text{ lb−in.} \quad f_{by} = \frac{M_{x-x}}{Z_{y-y}} = \frac{20{,}565\text{ lb−in.}}{2.61\text{ in.}^3} = 7{,}879\text{ psi}$$

- Interaction of bending demand in the strong and weak axis

$$\left|\frac{f_{bx}}{F_b} + \frac{f_{by}}{F_b}\right| = \left|\frac{17{,}417\text{ psi}}{41{,}400\text{ psi}} + \frac{7{,}879\text{ psi}}{41{,}400\text{ psi}}\right| = 0.611 \leq 1.0 \qquad \text{OK}$$

Proportioning and Design: Supporting Frame

Support Frame Braces

- Maximum brace force occurs when loads are resisted by two braces.
- Horizontal force:

$$V_{brace} = \frac{E_{h,ves}+E_{h,sup}}{2\text{ braces}} = \frac{3{,}808\text{ lb}+762\text{ lb}}{2\text{ braces}} = 2{,}285\text{ lb/brace}$$

- Length of the brace: $L = \sqrt{(5\text{ ft})^2 + (6\text{ ft})^2} = 7.81\text{ ft}$
- Tension force in the brace:

$$T_u = \left(\frac{7.81\text{ ft}}{6\text{ ft}}\right)(2{,}285\text{ lb}) = 2{,}974\text{ lb} \qquad \text{(tension)}$$

- Nominal tensile capacity of 5/8-inch-diameter ASTM A307 threaded rods: $\phi r_n = 10{,}400\text{ lb}$
- Threaded rods are adequate, $\phi r_n > T_u$, $10{,}400\text{ lb} > 2{,}974\text{ lb}$ →OK

Proportioning and Design: Supporting Frame

Support Frame Columns

- HSS2x2x1/4 columns support vertical loads from vessel and frame. Column length, $L = 5$ ft.
- Overturning moment:

$$M = (10.5\text{ ft})(E_{h,ves}) + (5.0\text{ ft})(E_{h,sup}) = (10.5\text{ ft})(3{,}808\text{ lb}) + (5.0\text{ ft})(762\text{ lb}) = 43{,}796\text{ lb–ft}$$

- Maximum *T-C* loads in the columns due to overturning, where $d = (6\text{ ft})\sqrt{2} = 8.48\text{ ft}$

$$P_{Eh,col} = \frac{M}{d} = \frac{43{,}796\text{ lb}-\text{ft}}{8.48\text{ ft}} = 5{,}161\text{ lb}$$

- The vertical gravity load in each leg is $P_{g,sup} = 1{,}500\text{ lb/support}$ and $P_{Ev,sup} = 360\text{ lb/support}$.
- The compression load on the columns is: $C_u = 1.2(P_{g,sup}) + P_{Ev,sup} + P_{Eh,col} = 7{,}321\text{ lb}$
- The tension load on the columns is: $C_u = 0.9(P_{g,sup}) - P_{Ev,sup} - P_{Eh,col} = -4{,}171\text{ lb}$
- The capacity of the HSS2x2x1/4 column is 38,300 lb. Therefore, it is adequate.

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Proportioning and Design: Supporting Frame

Anchor Bolts

- The combination that results in net tension on the anchors will govern. Thus, the Load Combination 7 including overstrength is applied: $0.9D - E_v + E_{mh}$ where $E_{mh} = \Omega_{0p} Q_E$
- Vertical design tension force:

$$T_u = 0.9(P_{g,sup}) - P_{Ev,sup} - \Omega_{0p} P_{Eh,col}$$

$$T_u = 0.9(1{,}500\text{ lb}) - 360\text{ lb} - (2.0)(5{,}161\text{ lb}) = -9{,}333\text{ lb}$$

- Horizontal design shear force:

$$V_u = \Omega_{0p} V_{Eh,col} = (2.0)(1{,}143\text{ lb}) = 2{,}285\text{ lb}$$

- When comparing the support frame column forces to the connection to the floor slab forces, the tension force increases by 124%, and the shear force increases by 100%.

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Questions?

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