FEMA P-2018: Seismic Evaluation of Older Concrete Buildings for Collapse Potential

William Holmes
Structural Engineer
Rutherford + Chekene

Dr. Jack Moehle
Professor
UC Berkeley

Dr. Abbie Liel
Professor
Univ Colorado

Dr. Rami Elhassan
Principal
IDS Group

FEMA

nehrp

1

FEMA P-2018: Introduction

Bill Holmes, Structural Engineer, Rutherford + Chekene

FEMA

nehrp

2

Poll

What is your experience with seismic evaluation of existing buildings?

- ❑Little or no experience
- ❑Familiar with ASCE/SEI 41
- ❑Experienced with ASCE/SEI 41
- ❑Experienced with ASCE/SEI 41 use on concrete buildings

3

Poll

What is your present knowledge of FEMA P-2018?

- ❑None
- ❑Brief Perusal
- ❑Tried it on one building
- ❑Experienced User

4

Training Agenda

- Mr. Holmes will give overview of document
- Dr. Moehle will describe concepts on the demand side
- Dr. Liel will describe concepts on the capacity side—and the rating methodology
- Dr. Moehle will go through Chapter 6 covering frames
- Dr. Liel will go through Chapter 7 covering wall-frames
- Dr. Elhassan will go through an example use.
- Mr. Holmes will describe the policy implications of the document

5

What are the goals of this training?

- Application of the method
  - Buildings included
  - Buildings not included
- What can you expect to get from a P 2018 analysis?
- What is in the book?
- How do I use it? Concentrating on frame and wall/frame buildings.

6

Many Participants

Lots of people involved including:

- FEMA
- Applied Technology Council
- Project Technical Committee
- Students and others assisting the PTC
- Independent reviewers (10 review meetings)

Prepared by

APPLIED TECHNOLOGY COUNCIL
201 Redwood Shores Parkway, Suite 240
Redwood City, California 94065
www.ATCouncil.org

Prepared for

FEDERAL EMERGENCY MANAGEMENT AGENCY
Michael Mahoney, Project Officer
Robert D. Hanson, Technical Monitor
Washington, D.C.

APPLIED TECHNOLOGY COUNCIL
Jon A. Heintz, Project Manager

PROJECT TECHNICAL COMMITTEE
William T. Holmes (Project Tech. Director)
Abbie Liel
Michael Mehrain
Jack P. Moehle
Peter Somers

WORKING GROUP MEMBERS
Saman A. Abdullah
Carlos Arteta
Supratik Bose
Panagiotis Galanis
Cody Harrington
Travis Marcilla
Pablo Parra
Siamak Sattar
Andreas Stavridis
Duy Vu To

PROJECT REVIEW PANEL
Terry Lundeen (Chair)
Michael Cochran
Gregory G. Deierlein
Ken Elwood
Josh Gebelein
Laura N. Lowes
Khalid Mosalam
Robert Pekelnicky
Pui-Shum Shing
Bill Tremayne
Fred Turner
John W. Wallace

7

Why FEMA P-2018?

- In 2005-2006 discussions within the Concrete Coalition included the observation that although most (75%) of this building type will fail standard seismic evaluations, and are very vulnerable to damage, only a relatively small percentage will cause severe life safety issues. Policy-wise, these dangerous ones are the ones that urgently need to be identified and mitigated ("exceptionally high-risk buildings").
- Existing seismic evaluation methods are pass/fail.
  - Too many buildings will fail "collapse prevention" standards.
  - Not practical to require all these buildings to be "fixed" at once.

  A method to measure relative risk was needed to "rank" buildings in an inventory.

8

Epitome of Exceptionally High-Risk Building

FEMA

nehrp

9

During development of FEMA P-2018, Method to identify exceptionally high-risk buildings evolved

- **Ranking of risk from older concrete buildings here is** related to the probability of building [story] collapse
  - Ratings: Continuous Scale Simplified Scale

Continuous Scale	Simplified Scale	
	>0.7	Exceptionally High Risk
0.1-0.9	0.3-0.7	High Risk
	<0.3	Lower Risk

  - Not intended to override ASCE 41, "pass-fail" of established (consensus) performance objectives
  - No "safe-enough" cut-off given (at least until considerable calibration can be done)
- Nonlinear analysis not required
- On average the same level of effort as ASCE/SEI 41 Tier 2

FEMA

nehrp

10

Some things to consider…

FEMA

nehrp

11

Column failure leading to axial failure

Izmit, Turkey, 1999

Photo courtesy of Jack Moehle

FEMA

nehrp

12

Column failure leading to implosion


Northridge, 1994

Photo courtesy of Jack Moehle

Pure gravity column, not drift tolerant, started this collapse.

13

Joint failures

Photo courtesy of Jack Moehle *Chi-Chi, Taiwan, 1999*

Northridge, 1994

14

Wall failure leading to overturning

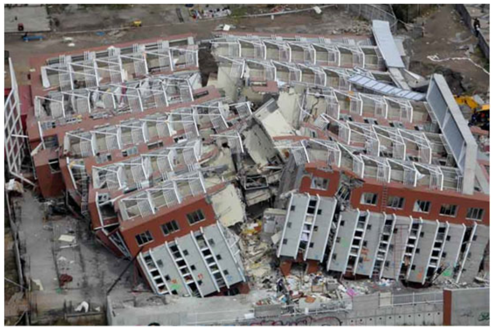


Photo courtesy of Jack Moehle

15

Wall failure leading to inward collapse

16

How are the ratings done?

- Estimate story drift demands with approximate methods
- Compare drift demands on vertical (gravity supporting) elements with drift capacities (D/C ratio)
  - Columns
  - Slab/column punching shear
  - Walls
  - Infill bays
- Estimate probability of collapse of the element based on this ratio
- Combine probability of collapse of all the element on one story to estimate the probability of collapse of the story.
- The story probability of collapse rounded to one decimal place (0.1-0.9) is the "rating."

Organization of Document

Chapter	Title	Topics of Interest
1	Introduction	Background, use, organization of report
2	Evaluation Methodology	Applicability, deficiencies not covered, building types not covered, overview of method
3	General Requirements	Data required, seismic hazard, load path
4	Component Strengths	Gravity loads, axial loads, load combinations, component strengths, column, wall story strengths, ratio of column/beam (slab) strength.
5	Structural Classification	Frame, wall-frame, bearing wall, and infill types, mechanism story strengths, period, lower risk and exceptionally high-risk buildings defined for "early out"
6	Frame Buildings	Full method for frames: includes method for demand and capacity of columns and punching of slabs; collapse probability as function of D/C
7	Wall-Frame Buildings	Parallel to chapter 6 for wall-frames. Incorporates possibility of wall collapse. Combines column and wall collapse for rating
8	Bearing Wall Buildings	Rating based on collapse probability of walls
9	Infill Frames	Includes methodology for infill mechanism analysis and infill collapse
10	Building Rating	Integrates "early-outs" with rated buildings
A-O	Appendices	Backup material for development of methodology

Appendices contain back-up development material

Appendix A: Development of Column Drift Capacities
Appendix B: Development of Method for Determining Column Ratings
Appendix C: Development of Method for Determining Story Ratings
Appendix D: Wall Strength Index (WSI) Method
Appendix E: Exceptionally Weak Building Criteria
Appendix F: Beam-Column Joints
Appendix G: Effective Fundamental Period
Appendix H: Development of Procedures to Estimate Story Drift Demands
Appendix I: Torsion Studies
Appendix J: Determination of Drift Factors
Appendix K: Archetype Building Analysis Methods
Appendix L: Frame and Wall Modeling Procedures
Appendix M: Column Shear Strength
Appendix N: Development of Wall Drift Capacities
Appendix O: Studies on Infilled Frames

Chapter 1

- Background and introductory material

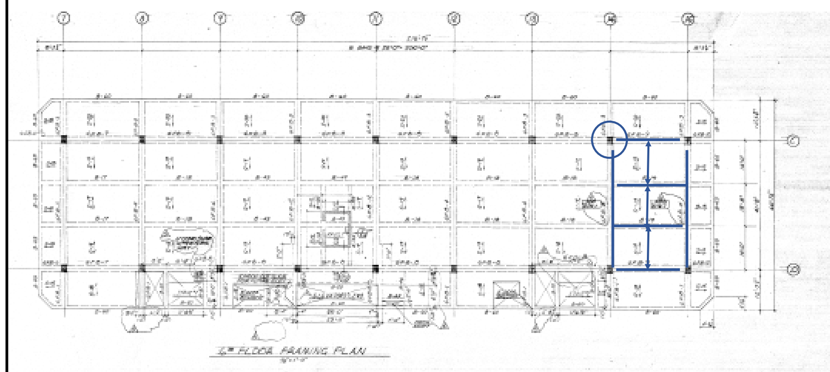
Chapter 2 Scope and Applicability

What kind of buildings need to be covered?
- Not only the lateral system (many don't have one)
- Also the gravity system

Following is a small sample of real buildings:

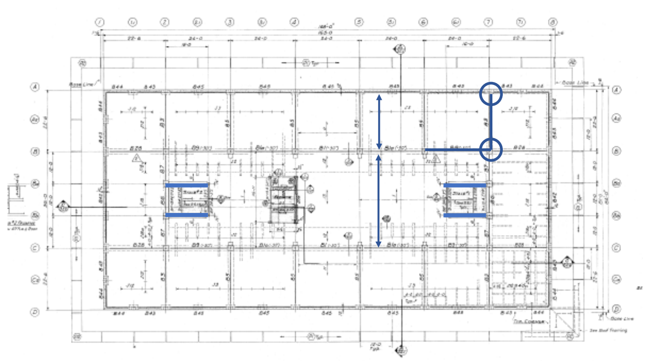
21

Columns, girders, beams, slabs



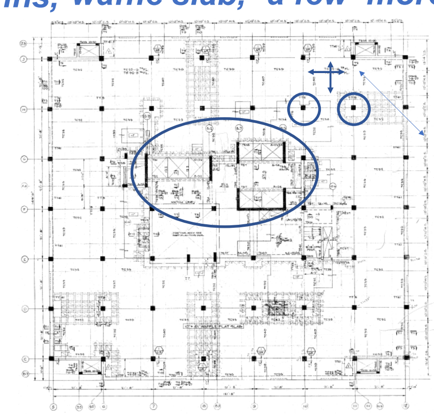
22

Columns, girders, pan joists, a few walls



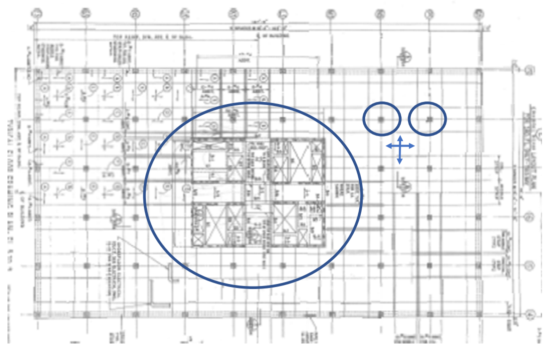
23

Columns, waffle slab, a few more walls



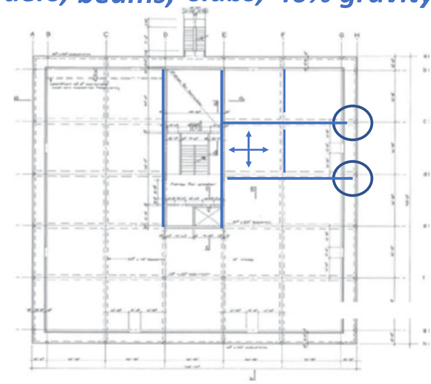
24

Columns, flat slabs, lots of wall



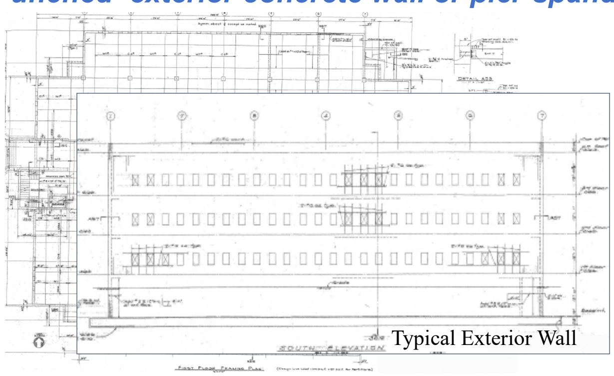
25

Columns, girders, beams, slabs, 40% gravity on two walls



26

Punched exterior concrete wall or pier-spandrel



27

Chapter 2 Scope and Applicability

Applicable

- Pure Frame Buildings
  - Beam column
  - Slab column
- Frame-Wall buildings
  - Both frame types with walls
  - Walls with openings (Pier/Spandrel)
- Bearing Wall Buildings
- Masonry Infill Frame Buildings

Not Applicable

- Greater than 160 ft tall
- Precast frame or wall with critical connections
- tilt-ups
- lift slabs
- residential bearing walls with precast slab diaphragms.

Not Considered

- Nonstructural issues
- Cladding falling hazards
- Prescriptive min R/F or foundation conditions
- Geologic Site Hazards

28

Chapter 3 General Requirements

- Drawings and/or knowledge of the structure
- Site investigation confirming as built conditions
- If no other guidance, default material properties from ASCE/SEI 41 may be used.
  - Physical testing not required but could result in better answer
- Complete load path required (guidance given)
- Seismic Hazard: ASCE/SEI 41-17 BSE-2E recommended

Chapter 4 Component Strengths

Important Chapter! Read before you start.

- Similar but not always the same as ASCE 41.
  - —Some simplifications
  - —Some conservatism removed
- For example
  - Structural demands/capacity at median
  - Reduced strength from inadequate splice length is considered for strength (in mechanism) (4.3.3.1) but not for calculation of Vp/Vn(4.4)
  - Transverse R/F spaced less than d is fully effective (unlike ASCE 41)
  - Some component strengths dependent on axial load. This chapter lists what axial load to use.

Chapter 5: the hub of the methodology

5.1 Introduction
5.2 Concrete Components
5.2.1 Reinforced Concrete Columns
5.2.2 Reinforced Concrete Structural Walls
5.3 Structural Classification of Buildings
5.3.1 Frame Structures
5.3.2 Frame-Wall Structures
5.3.3 Bearing Wall Structures
5.4 Wall Index and Wall Strength Index
5.4.1 Wall Index
5.4.2 Wall Strength Index
5.5 Effective Yield Strength
5.5.1 Plastic Mechanism Base-Shear Strength for Frames and Walls
5.5.4 Adjustment of Plastic Mechanism Base-Shear Strength for P-Delta
5.5.5 Base Shear Ratio
5.6 Effective Fundamental Period
5.7 Global Demand-to-Capacity Ratio
5.8 Identification of Lower Seismic Risk Buildings
5.9 Identification of Exceptionally High Seismic Risk Buildings
5.9.1 Exceptionally Weak Buildings
5.9.2 Buildings with Extreme Torsion
5.9.3 Discontinuous Walls Supported on Columns or Girders
5.10 Pounding

Chapter 5: the hub of the methodology

5.1 Introduction
5.2 Concrete Components
5.2.1 Reinforced Concrete Columns
5.2.2 Reinforced Concrete Structural Walls
5.3 Structural Classification of Buildings
5.3.1 Frame Structures
5.3.2 Frame-Wall Structures
5.3.3 Bearing Wall Structures

Identify structure-type

5.4 Wall Index and Wall Strength Index
5.4.1 Wall Index
5.4.2 Wall Strength Index
5.5 Effective Yield Strength
5.5.1 Plastic Mechanism Base-Shear Strength for Frames and Walls
5.5.4 Adjustment of Plastic Mechanism Base-Shear Strength for P-Delta
5.5.5 Base Shear Ratio
5.6 Effective Fundamental Period
5.7 Global Demand-to-Capacity Ratio
5.8 Identification of Lower Seismic Risk Buildings
5.9 Identification of Exceptionally High Seismic Risk Buildings
5.9.1 Exceptionally Weak Buildings
5.9.2 Buildings with Extreme Torsion
5.9.3 Discontinuous Walls Supported on Columns or Girders
5.10 Pounding

Chapter 5: the hub of the methodology

Tests included to default very good or very poor buildings out of extensive procedure. Rating assigned in Chapter 10

Chapter 5: the hub of the methodology

5.1 Introduction
5.2 Concrete Components
5.2.1 Reinforced Concrete Columns
5.2.2 Reinforced Concrete Structural Walls
5.3 Structural Classification of Buildings
5.3.1 Frame Structures
5.3.2 Frame-Wall Structures
5.3.3 Bearing Wall Structures
5.4 Wall Index and Wall Strength Index
5.4.1 Wall Index
5.4.2 Wall Strength Index
5.5 Effective Yield Strength
5.5.1 Plastic Mechanism Base-Shear Strength for Frames and Walls
5.5.4 Adjustment of Plastic Mechanism Base-Shear Strength for P-Delta
5.5.5 Base Shear Ratio
5.6 Effective Fundamental Period
5.7 Global Demand-to-Capacity Ratio
5.8 Identification of Lower Seismic Risk Buildings
5.9 Identification of Exceptionally High Seismic Risk Buildings
5.9.1 Exceptionally Weak Buildings
5.9.2 Buildings with Extreme Torsion
5.9.3 Discontinuous Walls Supported on Columns or Girders
5.10 Pounding

Mechanism Analysis: Leads to
- Lateral Strength
- Period, Teff
- Displacement Demand

Story collapse calculations in Chapters 6 (Frames)
7 (Wall Frames)
8 (Bearing Walls)
9 (Infill Frames)

Typical Flow Chapters 6,7,8 and 9

1. Using T_{eff} and site spectral demand, calculate spectral displacement similar ASCE 41
2. Calculate story/component drifts based on
   a) Spectral Displacement
   b) Tabularized story alpha factors based on controlling mechanism
3. Calculate column (or other gravity element) drift capacity
4. Get "collapse rating" (based on probability of collapse) of gravity supporting elements based on drift demand/capacity ratios
5. Convert individual ratings to story rating (based on probability of 25% loss of gravity support).

Chapter 10 Building Ratings

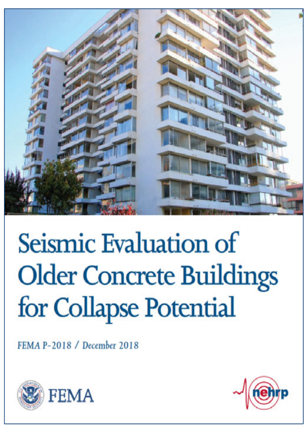
- Building Rating is taken as highest (worst) story rating in either direction.
- Chapter combines category assignments ("early outs") and numerical ratings into three groups:
  - Lower seismic risk (<0.3)
    High seismic risk (0.3-0.7)
    Exceptionally high seismic risk (>0.7)
- Groups can then be set as priorities for mitigation (or further study) or
- Individual ratings can be used to further refine priorities

37

Many specific deficiencies covered

- In addition to overall collapse methodology, consideration of many localized deficiencies are incorporated into ratings:
  - Discontinuous columns
  - Discontinuous walls
  - Corner beam-column joints
  - Slab frame story collapse from either columns or punching shear
  - Pier spandrel condition (frame? or wall?)
  - Pounding
  - Inadequate splices

38



- It is free and electronically available via this link: https://www.fema.gov/sites/default/files/2020-08/fema_seismic-eval-older-concrete-buildings_p-2018.pdf
- Participants in the U.S. may request a free hard copy be mailed to them by emailing FEMA's publication office: FEMAPubs@gpo.gov

39

Questions?

40

FEMA P-2018: Mechanism Analysis and Drift Demands

Jack Moehle, University of California, Berkeley

FEMA

nehrp

1

Chapter 5: the hub of the methodology

Mechanism Analysis: Leads to
- Lateral Strength
- Period, T_e
- Demand-to-Capacity Ratio
- Displacement Demand (Ch 6 & 7)

FEMA

nehrp

2

Effective yield strength, $V_y = V_{p1}$ (5.5)

Definition: The base-shear strength under static lateral loading, considering expected member strengths, calculated along each principal direction of the building.

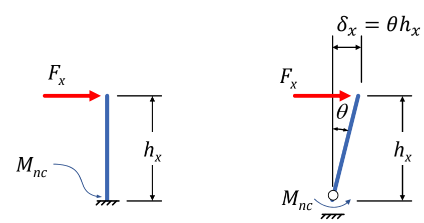
Methods: 1) Simplified mechanism analysis (typical method)
2) Nonlinear static analysis (if results available)

FEMA

nehrp

3

Principle of virtual displacements



(a) Real structure and forces

(b) Virtual displacements

$$F_x\delta_x - M_{nc}\theta = 0$$

$$F_x\delta_x = M_{nc}\theta \quad (i.e., W_{ext} = W_{int})$$

$$F_x = \frac{M_{nc}\theta}{\delta_x} = \frac{M_{nc}}{h_x}$$

(c) Virtual work solution

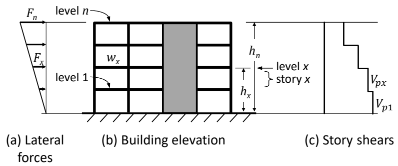
Principle of virtual displacements: For a body in equilibrium, the work done by forces as they move through any compatible displacement is zero.

FEMA

nehrp

4

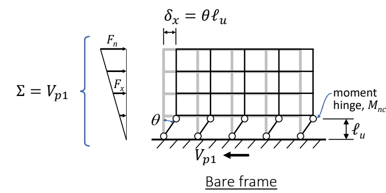
Definitions (5.5.1)



$F_x = C_{vx}V_{p1}$, where $C_{vx} = \frac{w_x h_x}{\sum_{i=1}^{n} w_i h_i}$ *(this is simplified from ASCE 41)*

$$V_{px} = \left(\sum_{i=x}^{n} C_{vi}\right) V_{p1}$$

Mechanism 1 (5.5.1)

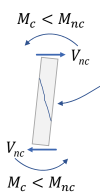


$$W_{ext} = W_{int}$$

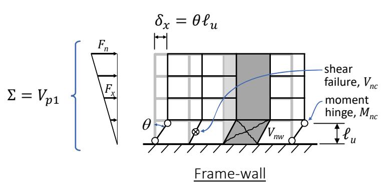
$$V_{p1}\delta_x = \sum M_{nc}\theta$$

$$V_{p1} = \frac{\theta}{\delta_x}\sum M_{nc} = \frac{1}{\ell_u}\sum M_{nc}$$

Mechanism 1 (5.5.1)



Member strength limited by shear strength

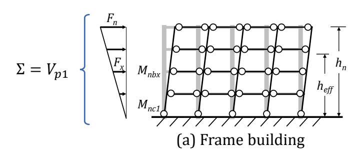


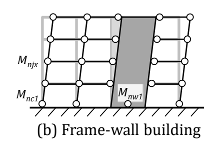
$$W_{ext} = W_{int}$$

$$V_{p1}\delta_x = \sum M_{nc}\theta + \sum V_{nc}\delta_x + \sum V_{nw}\delta_x$$

$$V_{p1} = \frac{1}{\ell_u}\sum M_{nc} + \sum V_{nc} + \sum V_{nw}$$

Mechanism 2 (5.5.1)





We could (a) write out the work equations, or
(b) use the following approximation.

$$V_{p1} = \frac{\sum M_{nc1} + \sum M_{nbx}}{h_{eff}}$$

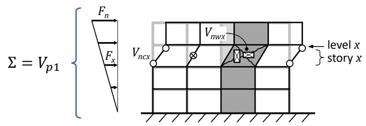
where $h_{eff} = 0.7h_n$

$$V_{p1} = \frac{\sum M_{nc1} + \sum M_{njx} + \sum M_{nw1}}{h_{eff}}$$

All moments are either nominal moment strengths M_n or moments limited by member shear strength (see previous slide).

Mechanism 3 (5.5.1)

req'd for vertically irregular framing

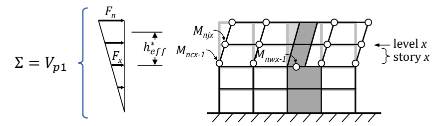


Vertically irregular structure

1. Find individual column strengths: $V_{ncx} = min[V_{nc}, \Sigma M_{nc}/\ell_u]$
2. Find wall shear strength: V_{nwx}
3. Find shear strength of story *x*: $V_{px} = \sum V_{ncx} + \sum V_{nwx}$
4. Scale to the base level: $V_{p1} = V_{px}/\sum_{i=x}^{n} C_{vi}$

Mechanism 4 (5.5.1)

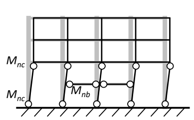
(req'd for vertically irregular framing)



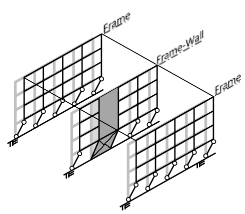
(a) Mechanism 4

1. Find individual column strengths: $V_{ncx} = min[V_{nc}, \Sigma M_{nc}/\ell_u]$
2. Find wall moment strength: M_{nwx-1} or moment limited by shear strength
3. Find shear strength of story *x*: $V_{px} = \frac{\sum M_{ncx-1} + \sum M_{njx} + \sum M_{nwx-1}}{h_{eff}^{*}}$
4. Scale to the base level: $V_{p1} = V_{px}/\sum_{i=x}^{n} C_{vi}$

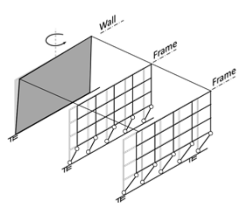
Other mechanisms (5.5.3, 5.5.4)



(a) Mezzanines



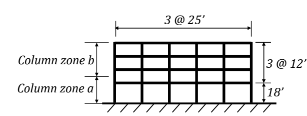
(b) 3-D considerations



(c) Plan torsion

Example

(a) Frame elevation



Total weight per frame is W = 3500 kips.

(b) Materials f_c' = 4000 psi, f_y = 60 ksi

(c) Member properties

Beams: 18" x 30", M_{nb}^{-} = 700 k-ft, M_{nb}^{+} = 350 k-ft, V_{nb} = 90 k, w_u = 2 klf

Columns: 24" x 24", M_{nca} = 1200 k-ft, M_{ncb} = 800 k-ft, V_{nca} = 110 k, V_{ncb} = 100k

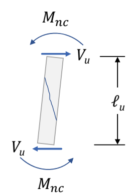
Joints: Interior deemed OK per FEMA P-2018.

Exterior: $V_{nj} = 10\sqrt{f_c'}\sqrt{\frac{h_c}{h_b}}A_j = 326\ k$ per FEMA P-2018, 4.3.3

Example continued

Are any member strengths limited by shear?

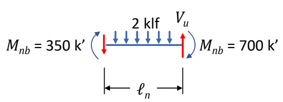
Columns



$$V_u = \frac{2M_{nc}}{\ell_u} = \frac{2 \times 1200\,k'}{18' - 1.25'} = 143\ kips > V_{nca} = 110\ kips$$

Therefore, first-story columns are shear-controlled.

Beams



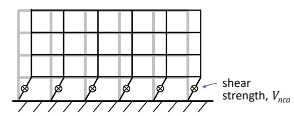
$$V_u = \frac{w_u \ell_n}{2} + \frac{\Sigma M_{nb}}{\ell_n} = 69\ kips < V_{nb} = 90\ kips$$

Therefore, beams are moment-controlled.

Note: We could also check whether beam strengths are limited by joint shear strengths, but we will skip that here. (They aren't.)

Example continued

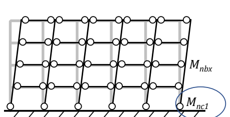
Mechanism 1



$$V_{p1} = \sum V_{nca} = 6 \times 110\ kips = 660\ kips$$

Example continued

Mechanism 2



$$V_{p1} = \frac{\sum M_{nc1} + \sum M_{nbx}}{h_{eff}} = \frac{6 \times 921k' + (350k' + 700k') \times 5 \times 4}{0.7 \times (18' + 3 \times 12')} = 702\ k$$

This value of 702 k exceeds V_{p1} = 660 k calculated for Mechanism 1. Therefore, Mechanism 1 will occur before Mechanism 2, so Mechanism 1 is the controlling mechanism.

Base-shear ratio is V_{p1}/W = 660/3500 = 0.19 (See 5.5.5)

M_{nc1} should not be taken larger than the moment corresponding to shear failure, so substitute $V_{nc} \times \frac{\ell_u}{2} = 110k \times \frac{16.75'}{2} = 921k'$ for M_{nc1}.

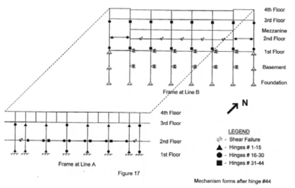
Chapter 5: the hub of the methodology

5.1 Introduction
5.2 Concrete Components
5.2.1 Reinforced Concrete Columns
5.2.2 Reinforced Concrete Structural Walls
5.3 Structural Classification of Buildings
5.3.1 Frame Structures
5.3.2 Frame-Wall Structures
5.3.3 Bearing Wall Structures
5.4 Wall Index and Wall Strength Index
5.4.1 Wall Index
5.4.2 Wall Strength Index
5.5 Effective Yield Strength
5.5.1 Plastic Mechanism Base-Shear Strength for Frames and Walls
5.5.5 Base Shear Ratio
5.6 Effective Fundamental Period
5.7 Global Demand-to-Capacity Ratio
5.8 Identification of Lower Seismic Risk Buildings
5.9 Identification of Exceptionally High Seismic Risk Buildings
5.9.1 Exceptionally Weak Buildings
5.9.2 Buildings with Extreme Torsion
5.9.3 Discontinuous Walls Supported on Columns or Girders
5.10 Pounding

Mechanism Analysis (5.5–5.5.5)

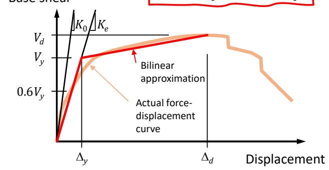
Next (5.6–5.9)

Effective fundamental period (5.6)



(a) Nonlinear static analysis (Degenkolb)

Effective fundamental period T_e based on K_e

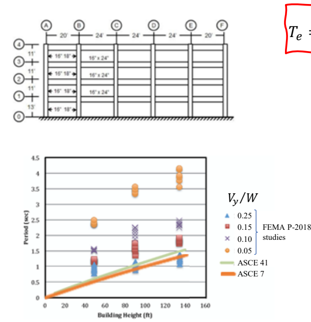


(b) Nonlinear static analysis pushover curve and effective stiffness K_e

Methods: 1) FEMA 2018 period equations (typical method)
2) Nonlinear static analysis (if results available)
Don't use ASCE 7 or linear elastic computer model to get T_e.

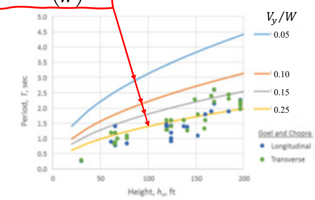
Effective fundamental period - frames (5.6)

(a) FEMA 2018 period study



(b) Comparison with field data

$$T_e = 0.07(h_n)^{0.5}\left(\frac{V_y}{W}\right)^{-0.5}$$

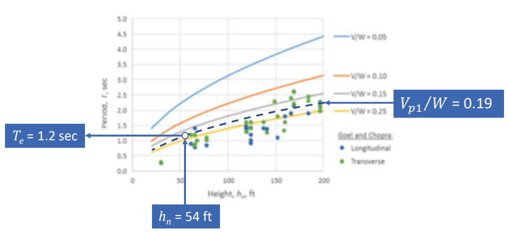


Effective fundamental period – Example (cont'd)

Back to our example frame: $T_e = 0.07(h_n)^{0.5}\left(\frac{V_y}{W}\right)^{-0.5}$

$= 0.07(54')^{0.5}(0.19)^{-0.5}$

$= 1.2$ sec



Effective fundamental period – walls and wall-frames (5.6)

Based on study by Goel and Chopra (1998), which is adopted by ASCE 7-16, but adjusted to represent reduced effective stiffness.

$$T_e = 0.0026h_n\frac{1}{\sqrt{C_w}}$$

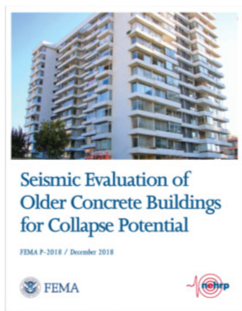
$$C_w = \frac{100}{A_B}\sum_{i=1}^{x}\left(\frac{h_n}{h_i}\right)^2\frac{A_i}{\left[1+0.83\left(\frac{h_i}{\ell_{wi}}\right)^2\right]}$$

where:

A_B = area of base of structure, ft²
A_i = web area of shear wall i in ft²
ℓ_{wi} = length of shear wall i in ft
h_i = height of shear wall i in ft
x = number of shear walls in the building effective in resisting lateral forces in the direction under consideration

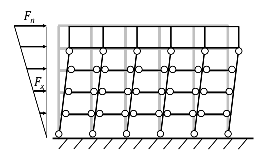
Effective fundamental period – other systems (5.6.1)

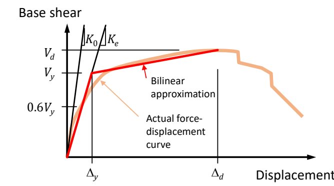
See FEMA 2018 for T_e for pier-spandrel systems and infilled frame systems.



Poll

From another job, you have results of a nonlinear static analysis available for a frame and would like to use them in FEMA P-2018. How can you use it?

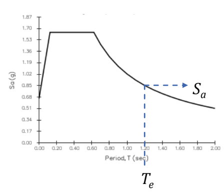


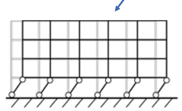


1) Can you use it to define the mechanism? (Y, N, Maybe)
2) Can you use it to define the base-shear strength, V_y? (Y, N, Maybe)
3) Can you use it to define the effective period, T_e? (Y, N, Maybe)

Global demand-capacity ratio, $\mu_{strength}$ (5.7)

$$\mu_{strength} = \frac{S_a}{V_y/W} C_m$$





From your mechanism analysis

Table 5-3 Values for Effective Mass Factor, C_m

No. of stories	Frame System	Wall or Frame-Wall System	Pier-Spandrel System	Infill Wall System
1-2	1.0	1.0	1.0	1.0
≥ 3	0.9	0.8	0.8	1.0

Note: C_m shall be taken as 1.0 if the fundamental period, T_e, in the direction under consideration is greater than 1.0 sec.

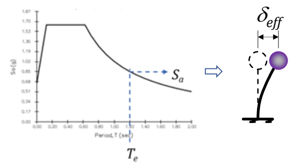
Quick outs (5.8)

Classification	Structural System	$\mu_{strength}$
Lower seismic risk	Frames with shear-critical columns (V_p/V_n > 0.6)	≤ 0.75
	All other cases	≤ 1.5
Exceptionally high seismic risk	Frames with shear-critical columns (V_p/V_n > 1.5)	> 2.0
	Frames without shear critical columns (V_p/V_n ≤ 0.6)	> 5.5
	Some discontinuous wall-on-column conditions	Any
	Some discontinuous wall-on-girder conditions	Any
	Some pounding conditions	Any

Story drift calculation (Chapters 6, 7, …)

25

Global seismic drift demand (6.4, 7.4, …)



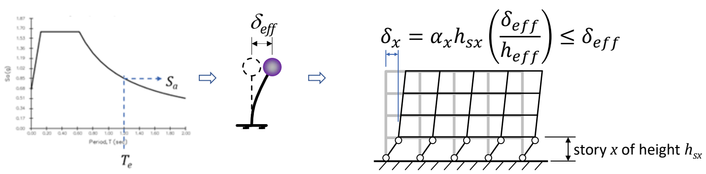
$$\delta_{eff} = C_1 C_2 S_a \frac{T_e^2}{4\pi^2} g$$

- δ_{eff}: Equivalent SDOF displacement
- C_1: Coefficient to amplify short-period drift (from ASCE 41) $C_1 = 1 + \frac{\mu_{strength} - 1}{aT_e^2}$
- C_2: Coefficient to amplify drift due to degradation (from ASCE 41) $C_2 = 1 + \frac{1}{800}\left(\frac{\mu_{strength} - 1}{T_e}\right)^2$
- $S_a \frac{T_e^2}{4\pi^2} g$: SDOF spectral displacement

(All from ASCE 41)

26

Story drift demand (6.5, 7.5, …)



$$\delta_x = \alpha_x h_{sx}\left(\frac{\delta_{eff}}{h_{eff}}\right) \le \delta_{eff}$$

27

Story drift demand (6.5, 7.5, …)

$$\delta_x = \alpha_x h_{sx}\left(\frac{\delta_{eff}}{h_{eff}}\right) \le \delta_{eff}$$

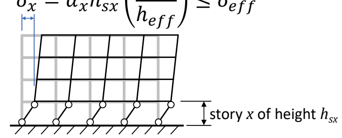


Table 6-1 Values of Coefficient α for Frame Systems

No. of Stories in the Building	Yield Mechanism[2]	Values of α[1]: Critical Stories	Values of α[1]: Other Stories[3]
1	(any)	1.0	(n/a)
2	1, 3	2.0	0.5
	2, 4	1.5	1.0
3-6	1, 3	2.0	$1-0.5\frac{x-2}{n-2}$
	2, 4	1.5	1.0
7-8	1, 3	*Linearly interpolate between the values for 6 and 9 stories*	
	2, 4	1.5	1.0
≥ 9	1, 3	2.5	1.5
	2, 4	1.5	1.0

(1) x is the story under consideration; n is the total number of stories.

(2) Where Mechanism 2 is calculated to be the controlling mechanism, but the calculated plastic mechanism base-shear strength for Mechanism 2 is three-quarters (3/4) or more of the calculated plastic mechanism base-shear strength for Mechanism 1, Mechanism 1 should be taken as the controlling mechanism for selection of α values.

(3) Values of α for "Other Stories" are generally not used, except where components in other stories are designated as critical because of increased local vulnerability, as required in Section 6.3.

For our example frame, the controlling mechanism is Mechanism 1, α_x = 2.0, h_{sx} = 18′, h_{eff} = 0.7 x 54′ = 38′.
Therefore, $\delta_x = 2.0 \times 18' \times (\delta_{eff}/38') = 0.95\delta_{eff}$.
In terms of drift ratio, if SDOF drift ratio is $\frac{\delta_{eff}}{h_{eff}} = 0.015$,
then the first-story drift ratio is $\frac{\delta_x}{h_{sx}} = 0.03$.

28

Adjustment for P-Δ

Only applicable to frame systems.

$$\delta_{x1} = \delta_x \left[\frac{1}{1 - \frac{W_x \delta_x}{V_{px} h_x}} \right]$$

δ_{x1} = story drift demand of story x amplified for P-delta effects

δ_x = story drift demand

W_x = gravity load, approximated as the seismic weight of the stories above level x

V_{px} = plastic mechanism shear strength at story x

h_x = height from the base of a building to level x

29

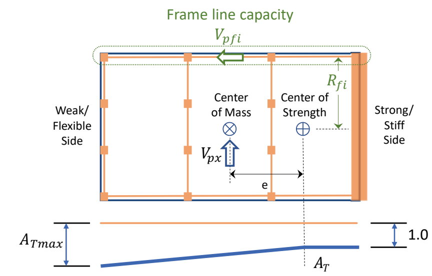
Adjustment for Torsion

Only applicable to wall or frame-wall systems.

$$TR = \frac{T_{Dx}}{T_{Cx}} = \frac{torsion\ demand}{torsion\ capacity}$$

$$T_{Dx} = V_{px} e$$

$$T_{Cx} = \sum_{i=1}^{n_f} |V_{pfi}||R_{fi}|$$



Drifts will be adjusted by factor A_T related to $A_{Tmax} = 2.75 \times TR + 0.5 \geq 1.0$

30

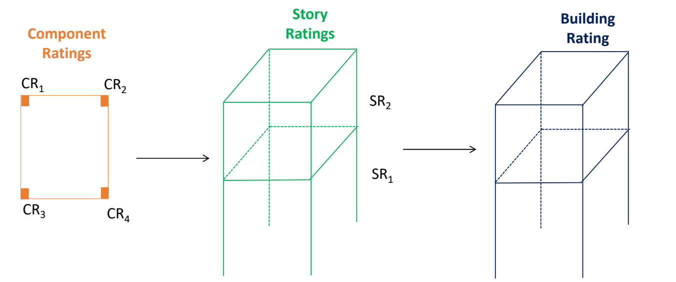
Questions?

31

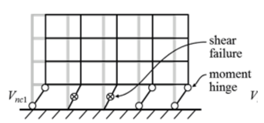
FEMA P-2018: Drift Capacities and Rating Systems

Abbie Liel, University of Colorado, Boulder

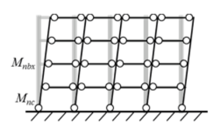
Overview



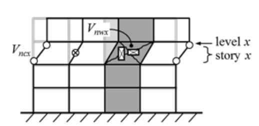
6.2 Identification of Critical Stories



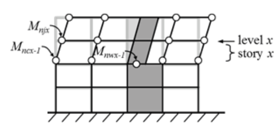
Mechanism 1: 1st story



Mechanism 2: 1st story



Mechanism 3: story where mechanism forms



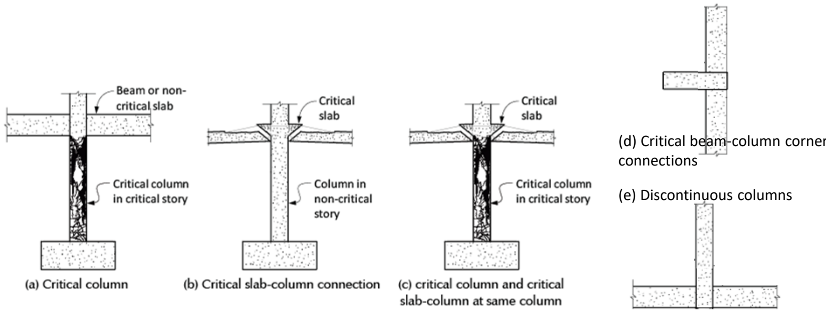
Mechanism 4: lowest story in which yielding occurs

Poll

What mechanism would you expect to be most common for frame buildings?

- ❑ Mechanism 1
- ❑ Mechanism 2
- ❑ Mechanism 3
- ❑ Mechanism 4

6.3 Identification of Critical Components



Types of critical components in frame systems

6.8 Component Ratings

Component ratings represents the probability that the drift demand exceeds the drift capacity.

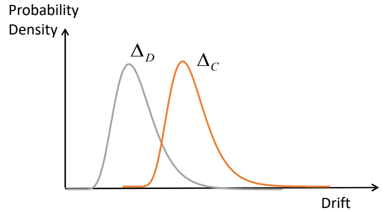


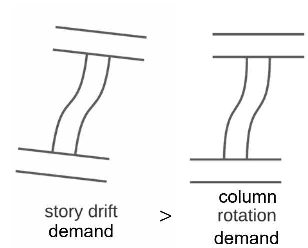
Illustration of structural reliability methods to assess probability that drift demand exceeds drift capacity

6.6 Drift Demands on Critical Components

- Story drift demands are converted to component drift demands based on:
  - Torsional amplification of drifts
  - Separation of story drifts attributable to each component

6.6.1 Rotation Demands on Critical Columns

- Need to convert <u>story drift</u> demand to a <u>column rotation</u> demand



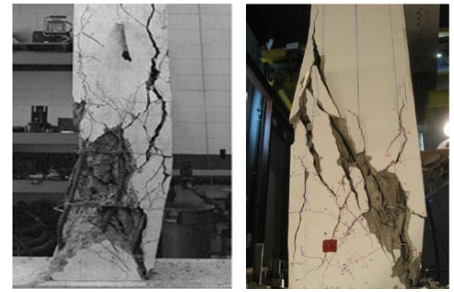
6.6.1 Rotation Demands on Critical Columns

Table 6-2 Drift Factor for Columns

Ratio of Column Strengths to Beam Strengths[2] $\sum M_c/\sum M_b$	Column Drift Factor γ
≤ 0.6	0.85
1	0.70
≥ 2.4	0.30

6.7.1 Column Drift Capacities

- Median column deformation capacity from empirical data



Examples of column tests

6.7.1 Column Rotation Capacities

- Parameters influencing rotation capacities
  - Failure mode
    - Flexure-critical columns tend to have greater rotation capacities
  - Axial load
    - Columns carrying higher axial loads tend to have lower rotation capacities
  - Transverse reinforcement
    - Columns with greater transverse reinforcement tend to have greater rotation capacities

6.7.1 Column Rotation Capacities

Table 6-2 Plastic Rotation Capacities for Tied Columns

Flexure-Critical Columns ($V_p/V_n \le 0.6$, $\rho_t > 0.002$, and $s/d < 0.5$)	
For $\left(\frac{P}{A_g f'_{ce}}\right) \ge 0.1$	$\theta_c = 11.4\rho_t + 0.034 - \left(\frac{P}{A_g f'_{ce}}\right)(14\rho_t + 0.036) \ge 0.0$
For $\left(\frac{P}{A_g f'_{ce}}\right) < 0.1$	$\theta_c = 10\rho_t + 0.03 \ge 0.0$
Flexure-Shear and Shear-Critical Columns (i.e., Columns not classified as Flexure-Critical Columns)	
For $\left(\frac{P}{A_g f'_{ce}}\right) \le 0.5$	$\theta_c = \frac{0.5}{5 + \frac{P}{0.8 A_g f'_{ce}} \frac{1}{\rho_t} \frac{f'_{ce}}{f_{ye}}} - 0.01 \ge \theta_{c,\min}$ $P/A_g f'_{ce}$ should not be taken smaller than 0.1
θ_c should be reduced linearly for $\left(\frac{P}{A_g f'_{ce}}\right) > 0.5$ from its value at $\left(\frac{P}{A_g f'_{ce}}\right) = 0.5$ to zero at $\left(\frac{P}{A_g f'_{ce}}\right) = 0.7$	
$\theta_{c,\min} = 0.042 - 0.023\left(\frac{P}{A_g f'_{ce}}\right) + 0.63\rho_t - 0.023\left(\frac{V_p}{V_n}\right) \ge 0.0$ $P/A_g f'_{ce}$ should not be taken smaller than 0.1	

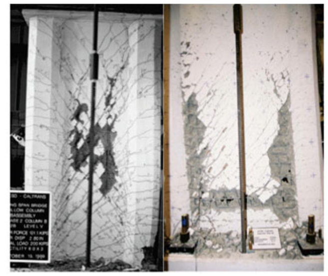
6.8 Column Ratings

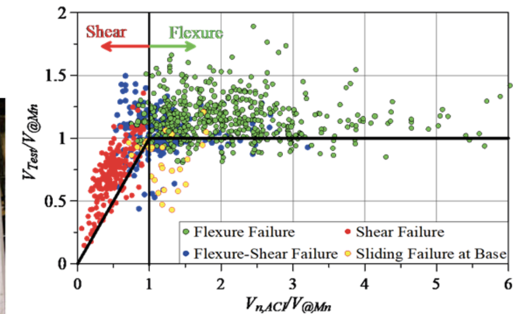
Table 6-6
Column Ratings

Drift Demand to Drift Capacity Ratio Δ_D/Δ_C	Column Rating *CR*
$\Delta_D/\Delta_C \leq 0.25$	0.0
$0.4 \geq \Delta_D/\Delta_C > 0.25$	0.1
$0.5 \geq \Delta_D/\Delta_C > 0.4$	0.2
$0.7 \geq \Delta_D/\Delta_C > 0.5$	0.3
$0.9 \geq \Delta_D/\Delta_C > 0.7$	0.4
$1.1 \geq \Delta_D/\Delta_C > 0.9$	0.5
$1.4 \geq \Delta_D/\Delta_C > 1.1$	0.6
$1.8 \geq \Delta_D/\Delta_C > 1.4$	0.7
$2.5 \geq \Delta_D/\Delta_C > 1.8$	0.8
$3.0 \geq \Delta_D/\Delta_C > 2.5$	0.9
$\Delta_D/\Delta_C > 3.0$	0.93

7.7.4 Wall Drift Capacities

- Empirical relationships developed based on UCLA RC walls database

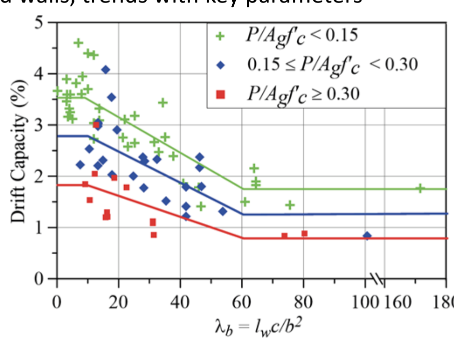




Example wall tests, and scatter plot of data

7.7.4 Wall Drift Capacities

- Flexure controlled walls, trends with key parameters

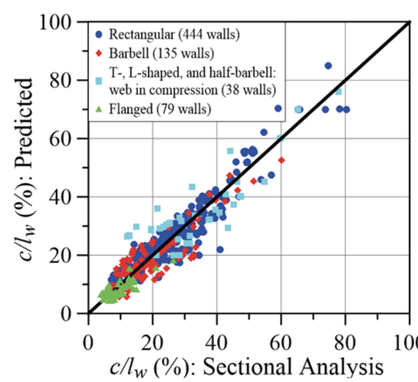


7.7.4 Wall Drift Capacities

- Determination of neutral axis depth

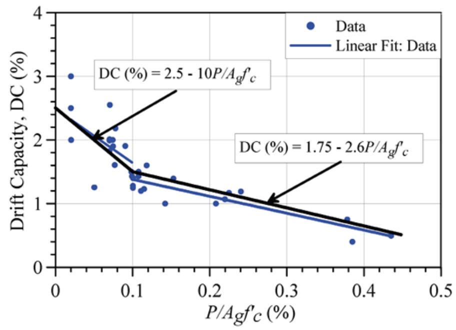
Table 7-8 Coefficients for Calculation of Neutral Axis Depth

Cross-Section	*a*	*b*
Rectangular	10	1.2
I-shaped and Barbell	3	1.4
T-shaped, L-shaped and Half-Barbell (web in compression)	30	0.7
T-shaped, L-shaped and Half-Barbell (web in tension)	20	2.0



7.7.4 Wall Drift Capacities

- Shear controlled walls, trends with key parameters



17

7.7.4 Wall Drift Capacities

Table 7-6 Drift Capacity of Flexure-Critical Walls

l_w/b_w (2)	c/l_w (2) 0.05	0.1	0.15	0.2	0.25	0.3	0.35	0.4	0.45	0.5	0.55	0.6
≤6	3.50	3.50	3.50	3.50	3.25	3.00	2.67	2.62	1.85	1.80	1.76	1.71
9	3.50	3.50	3.42	3.28	3.00	2.50	2.20	2.00	1.34	1.24	1.14	1.04
12	3.50	3.35	3.09	2.84	2.59	2.00	1.54	1.32	1.00	0.75	0.75	0.75
15	3.46	3.06	2.67	2.28	1.88	1.75	1.50	1.25	1.00	0.75	0.75	0.75
18	3.28	2.72	2.15	1.75	1.75	1.50	1.25	1.00	0.75	0.75	0.75	0.75
21	3.08	2.31	1.75	1.75	1.50	1.25	1.25	1.00	0.75	0.75	0.75	0.75
24	2.84	1.83	1.75	1.75	1.50	1.25	1.25	1.00	0.75	0.75	0.75	0.75
27	2.57	1.75	1.75	1.75	1.50	1.25	1.25	1.00	0.75	0.75	0.75	0.75
30	2.28	1.75	1.75	1.75	1.50	1.25	1.25	1.00	0.75	0.75	0.75	0.75
>35	1.75	1.75	1.75	1.75	1.50	1.25	1.25	1.00	0.75	0.75	0.75	0.75

+25% for columns with confined boundary elements

18

7.7.4 Wall Drift Capacities

Table 7-7 Drift Capacity of Shear-Critical Walls

$P/A_g f'_c$ (2)	Drift Capacity (%)
0.0	4.00
0.005	3.50
0.01	3.00
0.03	2.30
0.05	2.00
0.10	1.50
0.15	1.25
0.20	1.00
0.30	0.75
0.40	0.60
0.50	0.45

+50% for columns with confined boundary elements

19

7.8 Wall Ratings

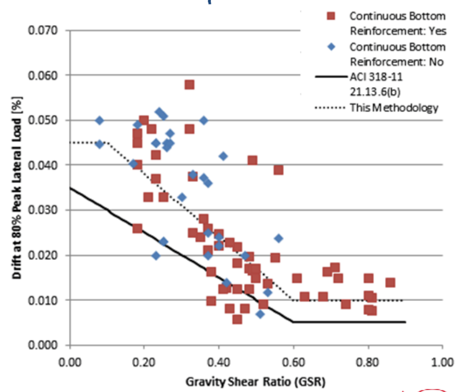
Table 7-10 Column Rating and Wall Rating

Drift Demand to Drift Capacity Ratio Δ_D/Δ_C	Column Rating, *CR* Wall Rating, *WR*
$\Delta_D/\Delta_C \leq 0.25$	0.0
$0.4 \geq \Delta_D/\Delta_C > 0.25$	0.1
$0.5 \geq \Delta_D/\Delta_C > 0.4$	0.2
$0.7 \geq \Delta_D/\Delta_C > 0.5$	0.3
$0.9 \geq \Delta_D/\Delta_C > 0.7$	0.4
$1.1 \geq \Delta_D/\Delta_C > 0.9$	0.5
$1.4 \geq \Delta_D/\Delta_C > 1.1$	0.6
$1.8 \geq \Delta_D/\Delta_C > 1.4$	0.7
$2.5 \geq \Delta_D/\Delta_C > 1.8$	0.8
$3.0 \geq \Delta_D/\Delta_C > 2.5$	0.9
$\Delta_D/\Delta_C > 3.0$	0.93

20

6.7.2 Slab-Column Connection Drift Capacities

- Based on database of slab-column tests
- Concerned with loss of vertical carrying capacity, so only with those that do not satisfy minimum requirements for structural integrity in terms of bottom reinforcement



6.7.2 Slab-Column Connection Drift Capacities

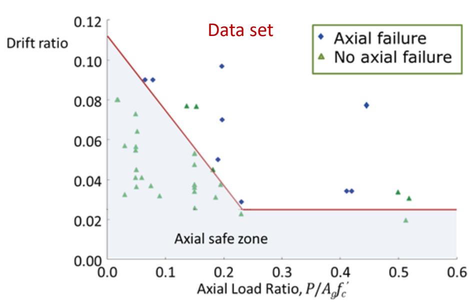
Tables 6-5 & 7-5 Drift Capacity of Critical Slab-Column Connections

Gravity Shear Ratio [2] V_g/V_c	Drift Capacity, Δ_c
≤ 0.1	$0.045h_{sx}$
≥ 0.6	$0.01h_{sx}$

Beam-Column Corner Connection Drift Capacities (6.7.3)

- Available data indicates corner beam-column joints can experience axial shortening/distress

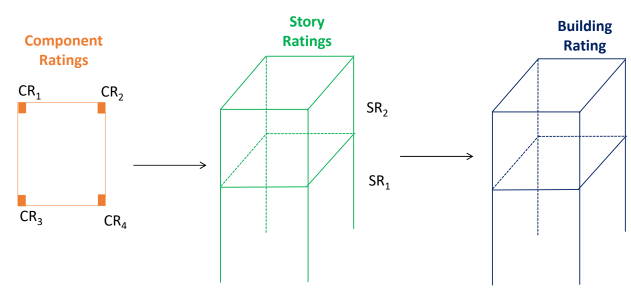
Data set



Implementation in methodology

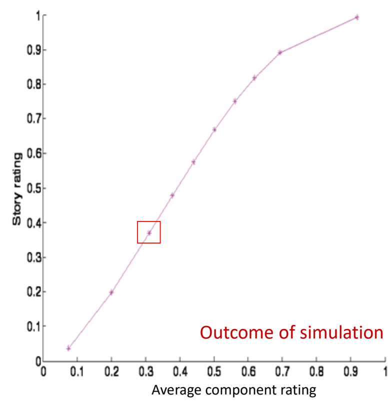
$$\Delta_c = \left(0.1 - 0.33\frac{P}{A_g f'_{ce}}\right) h_{sx}$$

6.9 Story Ratings



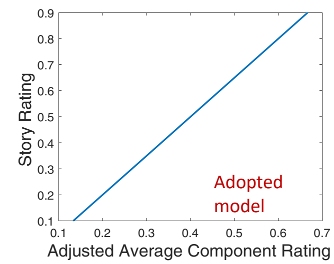
6.9 Story Ratings

- What combination of component ratings produces story failure?
  - Derivation involved probabilistic (Monte Carlo) simulation to determine story ratings, based on column (wall) ratings
  - Story failure occurs if components carrying 25% of gravity load in a story fail



6.9 Story Ratings

- Story ratings are function of component gravity loads, variability and component ratings



$$SR = 1.5R_{adj} - 0.1$$

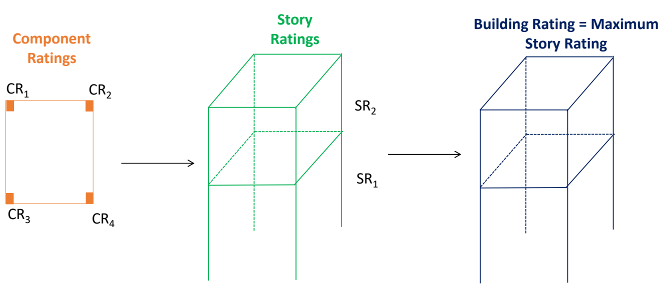
The adjusted average column in the story, R_{adj}, is defined as:

$$R_{adj} = R_{avg} + 0.625R_{avg}(\mathrm{COV} - 0.4)$$

where:

$$R_{avg} = \sum_{i=1}^{n_{col}} f_{col,i} CR_i$$

10 Building Ratings



Questions?

FEMA P-2018: Evaluation Procedures for Frame Systems

Abbie Liel, University of Colorado, Boulder

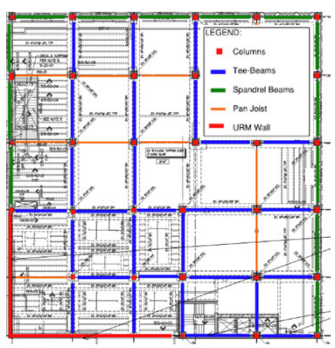
Ch 6 – Evaluation Procedures for Frame Systems

5. Frame system definition, strength and period calculations
6.2 Identify critical stories
6.3 Identify critical components
6.4 Calculate global seismic drift demand
6.5 Calculate story drift demand, including P-Delta
6.6 Calculate drift demands on critical components
6.7 Calculate drift capacities of critical components
6.8 Determine column ratings
6.9 Determine story ratings
10. Determine building

Chp. 6 (covers 6.2 through 6.9)

What is a Frame System?

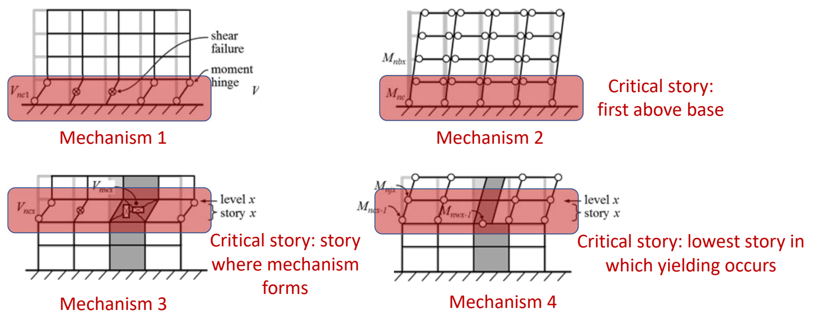
- Frame systems are systems composed of frames without structural walls or effective infill walls (5.3.1)
- Structural walls are defined based on thickness, reinforcement ratios, anchorage to floor diaphragms, and sufficient strength (5.2.2)



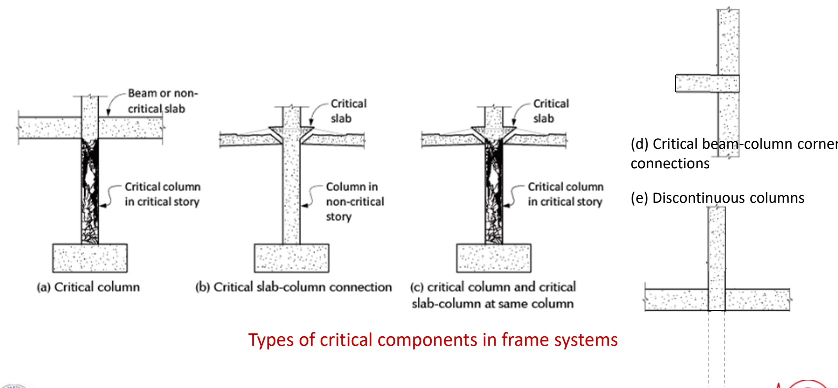
Before Chapter 6

- You will have already determined in Chapter 5
  - Effective yield strength using component strengths from Chapter 4 and identify controlling building mechanism
  - Effective fundamental period
  - Building is not essentially elastic or exceptionally weak

6.2 Identify Critical Stories



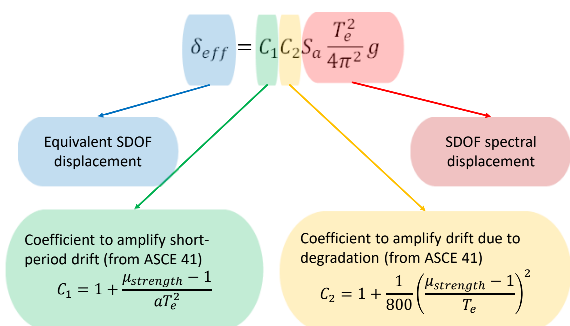
6.3 Identify Critical Components



Types of critical components in frame systems

6.4 Calculate Global Seismic Drift Demand

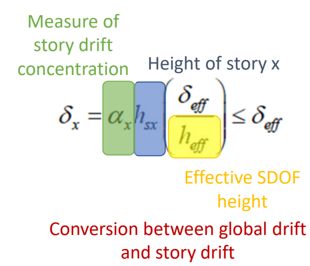
Displacement calculated for equivalent single degree of freedom system



6.5 Calculate Story Drift Demand

Alpha coefficients for frames, Table 6-1

No. of Stories in the Building	Yield Mechanism[2]	Critical Stories
1	(any)	1.0
2	1, 3	2.0
	2, 4	1.5
3-6	1, 3	2.0
	2, 4	1.5
7-8	1, 3	Linearly interpolate
	2, 4	1.5
≥ 9	1, 3	2.5
	2, 4	1.5



6.5.1 Calculate Story Drift Demand

- For frame systems, story drifts are increased to account for P-delta

$$\delta_{x1} = \delta_x \left[\frac{1}{1 - \frac{W_x \delta_x}{V_{px} h_x}} \right]$$

Amplified story drift

Gravity load above level x

Height from base of building to level x

Plastic mechanism shear strength at story x

6.6 Calculate Drift Demands on Critical Components

- Torsion: generally negligible for frames
- Drifts on columns should be reduced to account for only the portion of the story drift demand attributable to column deformations:

  component drift = γ x story drift

Drift factors for columns, Table 6-2

Ratio of Column Strengths to Beam Strengths[(2)] $\Sigma M_c / \Sigma M_b$	Column Drift Factor γ
≤ 0.6	0.85
1	0.70
≥ 2.4	0.30

6.7 Calculate Drift Capacity of Critical Components

- Drift capacity of columns

$$\Delta_c = l_u(\theta_c + 0.01)$$

Drift capacity

Clear height of column

Plastic rotation capacity + assumed "elastic" rotation

6.7 Calculate Drift Capacity of Critical Components

- Plastic rotation capacity of columns, θ_c

Plastic rotation capacities for tied columns, Table 6-3

Flexure-Critical Columns ($V_p/V_n \le 0.6$, $\rho_t > 0.002$, and $s/d < 0.5$)	
For $\left(\frac{P}{A_g f'_{ce}}\right) \ge 0.1$	$\theta_c = 11.4\rho_t + 0.034 - \left(\frac{P}{A_g f'_{ce}}\right)(14\rho_t + 0.036) \ge 0.0$
For $\left(\frac{P}{A_g f'_{ce}}\right) < 0.1$	$\theta_c = 10\rho_t + 0.03 \ge 0.0$
Flexure-Shear and Shear-Critical Columns (i.e., Columns not classified as Flexure-Critical Columns)	
For $\left(\frac{P}{A_g f'_{ce}}\right) \le 0.5$	$\theta_c = \frac{0.5}{5 + \frac{P}{0.8 A_g f'_{ce}} \frac{1}{\rho_t} \frac{f'_{ce}}{f_{ye}}} - 0.01 \ge \theta_{c,min}$ $P/A_g f'_{ce}$ should not be taken smaller than 0.1
θ_c should be reduced linearly for $\left(\frac{P}{A_g f'_{ce}}\right) > 0.5$ from its value at $\left(\frac{P}{A_g f'_{ce}}\right) = 0.5$ to zero at $\left(\frac{P}{A_g f'_{ce}}\right) = 0.7$	
$\theta_{c,min} = 0.042 - 0.023\left(\frac{P}{A_g f'_{ce}}\right) + 0.63\rho_t - 0.023\left(\frac{V_p}{V_n}\right) \ge 0.0$ $P/A_g f'_{ce}$ should not be taken smaller than 0.1	

6.7 Calculate Drift Capacity of Critical Components

- Plastic rotation capacity of columns, θ_c

Plastic rotation capacities for spiral-reinforced columns, Table 6-4

Flexure-Critical Columns ($V_p/V_n \le 0.6$, $\rho_t > 0.002$, and $s/d < 0.5$)	
For $\left(\frac{P}{A_g f'_{ce}}\right) \ge 0.1$	$\theta_c = 1.15\left[11.4\rho_t + 0.034 - \left(\frac{P}{A_g f'_{ce}}\right)(14\rho_t + 0.036)\right] \ge 0.0$
For $\left(\frac{P}{A_g f'_{ce}}\right) < 0.1$	$\theta_c = 1.15[10\rho_t + 0.03] \ge 0.0$
Flexure-Shear and Shear-Critical Columns (i.e., Columns not classified as Flexure-Critical Columns)	
For $\left(\frac{P}{A_g f'_{ce}}\right) \le 0.5$	$\theta_c = \frac{0.65}{5 + \frac{P}{0.8 A_g f'_{ce}} \frac{1}{\rho_t} \frac{f'_{ce}}{f_{ye}}} - 0.01 \ge \theta_{c,min}$ $P/A_g f'_{ce}$ should not be taken smaller than 0.1
θ_c should be reduced linearly for $\left(\frac{P}{A_g f'_{ce}}\right) > 0.5$ from its value at $\left(\frac{P}{A_g f'_{ce}}\right) = 0.5$ to zero at $\left(\frac{P}{A_g f'_{ce}}\right) = 0.7$	
$\theta_{c,min} = 0.06 - 0.06\left(\frac{P}{A_g f'_{ce}}\right) + 1.3\rho_t - 0.037\left(\frac{V_p}{V_n}\right) \ge 0.0$ $P/A_g f'_{ce}$ should not be taken smaller than 0.1	

6.7 Calculate Drift Capacity of Critical Components

- Drift capacity of slab-column connections

Table 6-5

Gravity Shear Ratio [(2)] V_g/V_o	Drift Capacity, Δ_c
≤ 0.1	$0.045h_{sx}$
≥ 0.6	$0.01h_{sx}$

Poll

True or false: A higher column rating indicates worse performance.

- ❑ True
- ❑ False

6.8 Determine Column Ratings

Table 6-6

Drift Demand to Drift Capacity Ratio Δ_D/Δ_C	Column Rating *CR*
$\Delta_D/\Delta_C \le 0.25$	0.0
$0.4 \ge \Delta_D/\Delta_C > 0.25$	0.1
$0.5 \ge \Delta_D/\Delta_C > 0.4$	0.2
$0.7 \ge \Delta_D/\Delta_C > 0.5$	0.3
$0.9 \ge \Delta_D/\Delta_C > 0.7$	0.4
$1.1 \ge \Delta_D/\Delta_C > 0.9$	0.5
$1.4 \ge \Delta_D/\Delta_C > 1.1$	0.6
$1.8 \ge \Delta_D/\Delta_C > 1.4$	0.7
$2.5 \ge \Delta_D/\Delta_C > 1.8$	0.8
$3.0 \ge \Delta_D/\Delta_C > 2.5$	0.9
$\Delta_D/\Delta_C > 3.0$	0.93

6.8 Determine Column Ratings

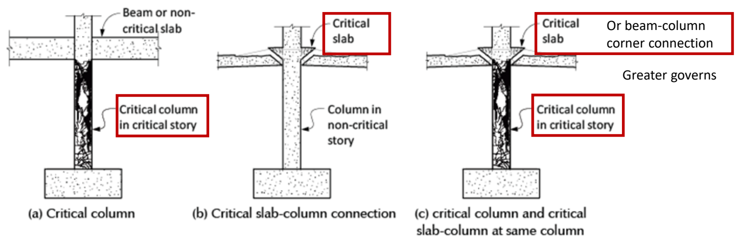
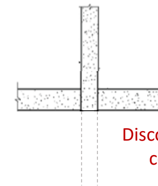


Illustration of components for which ratings are required

6.8.1 Determine Column Ratings

- Discontinuous columns supported by a beam or slab that is not a cantilever, CR = 0.8



Discontinuous column

6.9 Determine Story Ratings

- Story ratings are function of component gravity loads, variability and component ratings

$$R_{avg} = \sum_{i=1}^{n_{col}} f_{col,i} CR_i$$

Average component rating, weighted by gravity load carried

$$R_{adj} = R_{avg} + 0.625 R_{avg}(COV - 0.4)$$

Adjustment to average based on coefficient of variation

$$SR = 1.5 R_{adj} - 1$$

Story rating

Building Ratings (Chp.10)

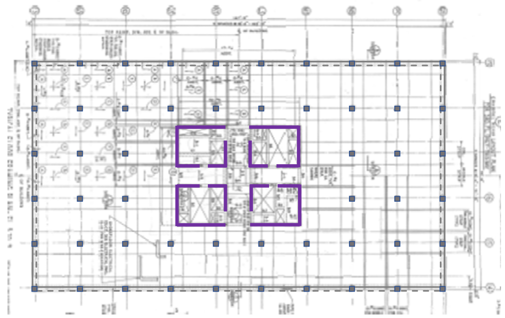
- Building rating is the worst story rating in either direction

$$BR = max(SR)$$

Questions?

FEMA P-2018: Evaluation Procedures for Frame-Wall Systems

Jack Moehle, University of California, Berkeley



1

Ch 7 - Evaluation Procedures for Frame-Wall Systems

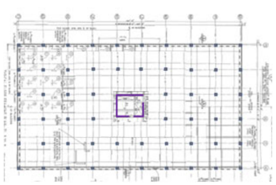
- Applicability
  - Systems with both frame lines and structural walls
  - Pier-spandrel systems are a subset of frame-wall systems
- Exclusions
  - Bearing wall systems (see Chapter 8)
  - Infilled frame systems (see Chapter 9)
  - Very thin and very lightly reinforced walls (see 5.2.2)

2

Ch 7 - Evaluation Procedures for Frame-Wall Systems

Building A

Building B



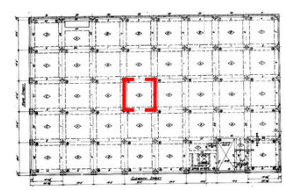
- Is it a frame or a frame-wall system?
  - Walls: 12" x 12', so these are walls per 5.2.2.
  - Check the ratio of wall area to total supported floor area $\frac{A_w}{A_f} = \frac{\Sigma Web\ areas\ in\ one\ direction}{Total\ supported\ floor\ area}$
    - Background studies in Appendix H suggest A_w/A_f around 0.0005 is sufficient for walls to dominate deformed shape provided the walls are *substantial* walls extending over building height.
    - For very small A_w/A_f, the calculated wall period (Equation 5-19) may exceed calculated frame period (Equation 5-18), which does not make sense.
    - Even a small wall can contribute to collapse problems, so check Chapter 7.
  - Judgment is required!

3

Poll

Consider the building shown.

Photograph



Typical Plan

N

2 Walls, 12" x 20'
A_w = 2 x 1' x 20' = 40 ft^2
Floor plan: 100' x 156'
A_f = 100' x 156' = 15,600 ft^2
A_w/A_f = 0.00051

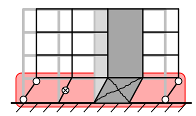
Which type of building should this be treated as?

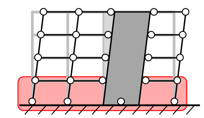
- ❑ a frame building (Chapter 6)
- ❑ a frame-wall building (Chapter 7)
- ❑ it depends

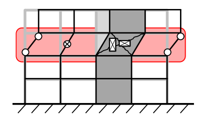
4

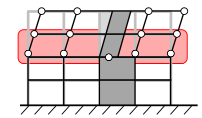
Ch 7 - Evaluation Procedures for Frame-Wall Systems

7.2 Identify Critical Stories


Mechanism 1


Mechanism 2


Mechanism 3

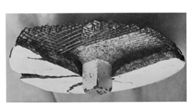

Mechanism 4

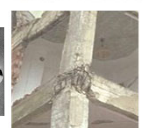
The *critical story* is the lowest story (or the only story) of the mechanism.

7.3 Identify Critical Components

- Columns
  - Any column in critical story
  - Column supporting discontinuous wall

- Walls in critical story
- Connections
  - Slab-column connections
  - Corner beam-column connections





7.4 Calculate Global Seismic Drift Demand

$$\delta_{eff} = C_1 C_2 S_a \frac{T_e^2}{4\pi^2} g$$

Drift calculated for equivalent single degree of freedom system

(All from ASCE 41)

7.5 Calculate Story Drift Demand

Table 7-1 Values of Coefficient α for Frame-Wall Systems

No. of Stories in the Building	Yield Mechanism[1]	Values of α: Critical Stories	Values of α: Other Stories[2]	
1	(any)	1.0	(n/a)	
2	1	1.4	0.5	
	2	1.2	1.0	
	3, 4	1.5	1.0	
≥3	1	$0.8h_{eff}/h_{sx}$	0.5	
	2	1.2	1.0	
	3	$0.8h_{eff}/h_{sx}$	0.5	
	4	1.5	*Stories below critical story*	0.5
			Stories above critical story	1.0

[1] Where Mechanism 2 is calculated to be the controlling mechanism, but the calculated plastic mechanism base-shear strength for Mechanism 2 is three-quarters (3/4) or more of the calculated plastic mechanism base-shear strength for Mechanism 1, Mechanism 1 should be taken as the controlling mechanism for selection of α values.

[2] Values of α for "Other Stories" are generally not used, except where components in other stories are designated as critical because of increased local vulnerability, as required in Section 7.3.

$$\delta_x = \alpha_x h_{sx}\left(\frac{\delta_{eff}}{h_{eff}}\right) \le \delta_{eff}$$

Conversion between global drift and story drift

Note: There is no P-delta adjustment for frame-wall systems.

9

7.6 Calculate Drift Demands on Critical Components

$$\Delta_D = A_T \gamma \delta_x$$

Amplification factor for plan torsion.

Reduction factor to represent fraction of story drift affecting critical component.

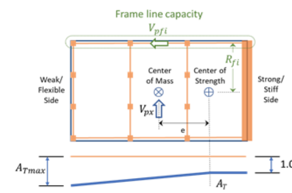


Table 7-2 Drift Factor, γ, for Columns

Ratio of Column Strengths to Beam Strengths, $\Sigma M_c/\Sigma M_b$	Column Drift Factor, γ
≤ 0.6	0.85
1.0	0.70
≥ 2.4	0.30

10

7.7 Calculate Drift Capacity of Critical Components

- Columns $\Delta_c = l_u(\theta_c + 0.01)$

Plastic rotation capacities for tied columns, Table 6-3

Flexure-Critical Columns ($V_p/V_n \le 0.6$, $\rho_t > 0.002$, and $s/d < 0.5$)	
For $\left(\frac{P}{A_g f'_{ce}}\right) \ge 0.1$	$\theta_c = 11.4\rho_t + 0.034 - \left(\frac{P}{A_g f'_{ce}}\right)(14\rho_t + 0.036) \ge 0.0$
For $\left(\frac{P}{A_g f'_{ce}}\right) < 0.1$	$\theta_c = 10\rho_t + 0.03 \ge 0.0$
Flexure-Shear and Shear-Critical Columns (i.e., Columns not classified as Flexure-Critical Columns)	
For $\left(\frac{P}{A_g f'_{ce}}\right) \le 0.5$	$\theta_c = \frac{0.5}{5 + \frac{P}{0.8 A_g f'_{ce}} \frac{1}{\rho_t} \frac{f'_{ce}}{f_{ye}}} - 0.01 \ge \theta_{c,min}$ $P/A_g f'_{ce}$ should not be taken smaller than 0.1
θ_c should be reduced linearly for $\left(\frac{P}{A_g f'_{ce}}\right) > 0.5$ from its value at $\left(\frac{P}{A_g f'_{ce}}\right) = 0.5$ to zero at $\left(\frac{P}{A_g f'_{ce}}\right) = 0.7$	
$\theta_{c,min} = 0.042 - 0.023\left(\frac{P}{A_g f'_{ce}}\right) + 0.63\rho_t - 0.023\left(\frac{V_p}{V_n}\right) \ge 0.0$ $P/A_g f'_{ce}$ should not be taken smaller than 0.1	

11

7.7 Calculate Drift Capacity of Critical Components

- Slab-column connections

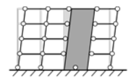
Table 7-5 Drift Capacity of Critical Slab-Column Connections without Continuous Bottom Bars through Column

Gravity Shear Ratio, V_g/V_c	Drift Capacity, Δ_c
≤ 0.1	$0.045h_{sx}$
≥ 0.6	$0.01h_{sx}$

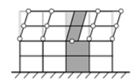
12

7.7 Calculate Drift Capacity of Critical Components

- Walls and vertical wall segments: flexure-controlled



Mechanism 2



Mechanism 4

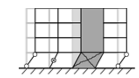
Table 7-6 Drift Capacity of Flexure-Critical Walls or Vertical Wall Segments (%)[1]

l_w/b_w[2]	c/l_w[2] 0.05	0.1	0.15	0.2	0.25	0.3	0.35	0.4	0.45	0.5	0.55	0.6
≤6	3.50	3.50	3.50	3.50	3.25	3.00	2.67	2.62	1.85	1.80	1.76	1.71
9	3.50	3.50	3.42	3.28	3.00	2.50	2.20	2.00	1.34	1.24	1.14	1.04
12	3.50	3.35	3.09	2.84	2.59	2.00	1.54	1.32	1.00	0.75	0.75	0.75
15	3.46	3.06	2.67	2.28	1.88	1.75	1.50	1.25	1.00	0.75	0.75	0.75
18	3.28	2.72	2.15	1.75	1.75	1.50	1.25	1.00	0.75	0.75	0.75	0.75
21	3.08	2.31	1.75	1.75	1.50	1.25	1.25	1.00	0.75	0.75	0.75	0.75
24	2.84	1.83	1.75	1.75	1.50	1.25	1.25	1.00	0.75	0.75	0.75	0.75
27	2.57	1.75	1.75	1.75	1.50	1.25	1.25	1.00	0.75	0.75	0.75	0.75
30	2.28	1.75	1.75	1.75	1.50	1.25	1.25	1.00	0.75	0.75	0.75	0.75
>35	1.75	1.75	1.75	1.75	1.50	1.25	1.25	1.00	0.75	0.75	0.75	0.75

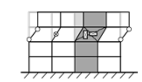
[1] For walls with confined boundaries, drift capacity may be increased by 25%.
[2] For intermediate values, drift capacity may be calculated using linear interpolation.

7.7 Calculate Drift Capacity of Critical Components

- Walls and vertical wall segments: shear-controlled



Mechanism 1



Mechanism 3

Table 7-7 Drift Capacity of Shear-Critical Walls or Vertical Wall Segments[1]

$P/A_g f'_c$[2]	Drift Capacity (%)
0.0	4.00
0.005	3.50
0.01	3.00
0.03	2.30
0.05	2.00
0.10	1.50
0.15	1.25
0.20	1.00
0.30	0.75
0.40	0.60
0.50	0.45

[1] For walls with confined boundaries, drift capacity may be increased by 50%.
[2] For intermediate values, drift capacity may be calculated using linear interpolation.

7.8 Determine Column and Wall Ratings

Table 7-10 Column Rating, *CR*, and Wall Rating, *WR*

Drift Demand to Drift Capacity Ratio Δ_D/Δ_C	Column Rating, *CR* Wall Rating, *WR*
$\Delta_D/\Delta_C \le 0.25$	0.0
$0.4 \ge \Delta_D/\Delta_C > 0.25$	0.1
$0.5 \ge \Delta_D/\Delta_C > 0.4$	0.2
$0.7 \ge \Delta_D/\Delta_C > 0.5$	0.3
$0.9 \ge \Delta_D/\Delta_C > 0.7$	0.4
$1.1 \ge \Delta_D/\Delta_C > 0.9$	0.5
$1.4 \ge \Delta_D/\Delta_C > 1.1$	0.6
$1.8 \ge \Delta_D/\Delta_C > 1.4$	0.7
$2.5 \ge \Delta_D/\Delta_C > 1.8$	0.8
$3.0 \ge \Delta_D/\Delta_C > 2.5$	0.9
$\Delta_D/\Delta_C > 3.0$	0.93

Determine Story Ratings (Section 7.9)

- Story ratings are function of component gravity loads, variability, and component ratings

$$R_{avg} = \sum_{i=1}^{n_{col}} f_{col,i} CR_i + \sum_{j=1}^{n_{wall}} f_{wall,j} WR_j$$

Average component rating, weighted by gravity load carried

$$R_{adj} = R_{avg} + 0.625 R_{avg}(COV - 0.4)$$

Adjustment to average based on coefficient of variation

$$SR = 1.5 R_{adj} - 1$$

Story rating

Chapter 10 Building Rating, BR

$$BR = \max SR$$

Questions?

FEMA P-2018: Example Application

Rami Elhassan, IDS Group

FEMA nehrp

1

Acknowledgment

I would like to acknowledge the contribution of Dr. Yangbo Chen, a Structural Engineer with IDS Group, in developing this presentation and in performing the analysis of this example building

2

Evaluation Procedure

1. Building Description - - *General*
2. Loads and Component Strengths - - *Chapter 4*
3. Plastic Mechanism Base-Shear Strength - - *Chapter 5*
4. Global Seismic Drift Demand - - *Chapter 6*
5. Drift Demand on Critical Story - - *Chapter 6*
6. Drift Demand on Critical Components - - *Chapter 6*
7. Drift Capacity of Critical Components - - *Chapter 6*
8. Critical Column Ratings - - *Chapter 6*
9. Story Rating - - *Chapter 6*
10. Building Rating - - *Chapter 10*

3

1. Building Description

- 5-Story Concrete Building
- Plan: 100’ N-S x 156’ E-W
- Typical story height 13’
  First: 17’
- Frames on three sides, and a solid concrete shearwall along the back (north) side
- N/S Direction classified as a **Frame** system, which will be presented herein

4

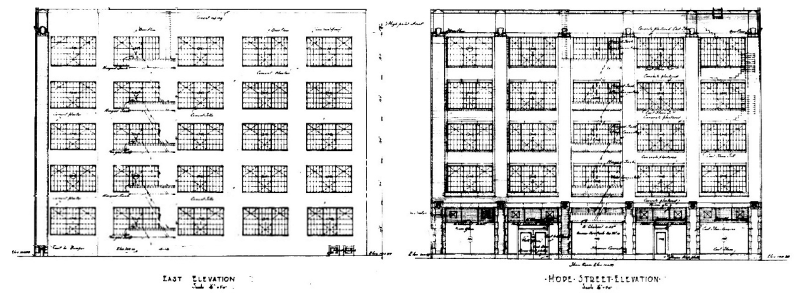
1. Building Description

- 5-Story Concrete Building
- Plan: 100’ N-S x 156’ E-W
- Typical story height 13’
  First: 17’
- Frames on three sides, and a solid concrete shearwall along the back (north) side
- N/S Direction classified as a **Frame** system, which will be presented herein

1. Building Description

East Elevation

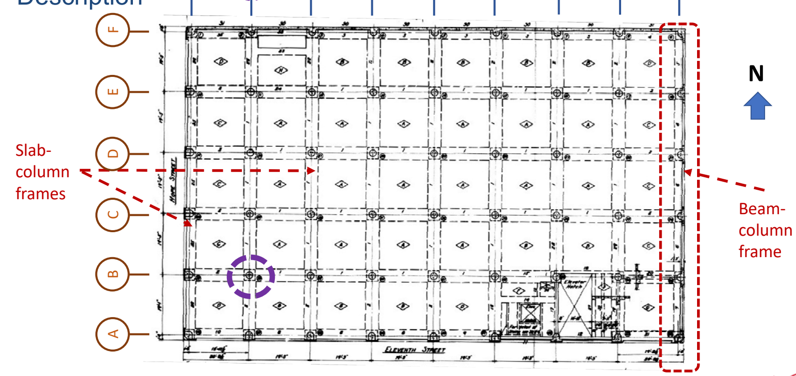
West Elevation



1. Building Description

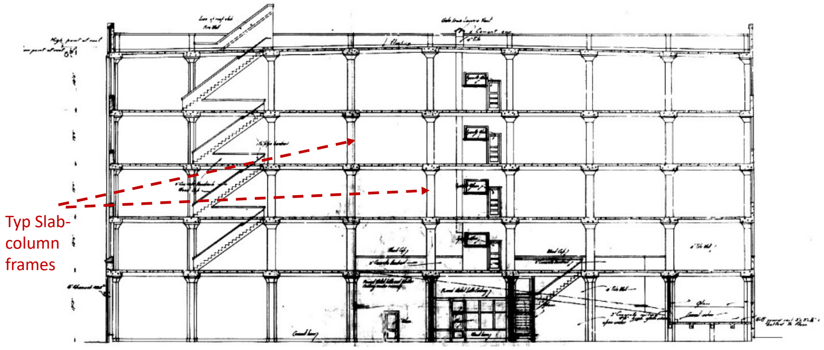
Typical Floor

1. Building Description

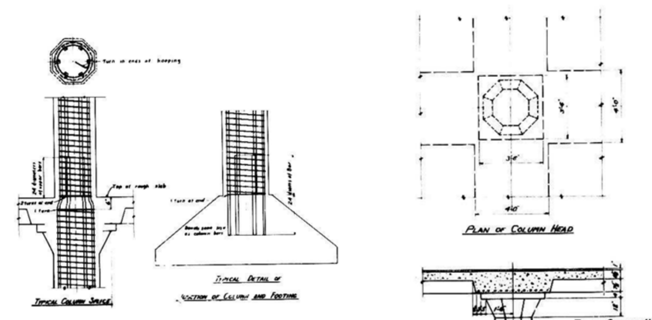


1. Building Description

Typical Building Section

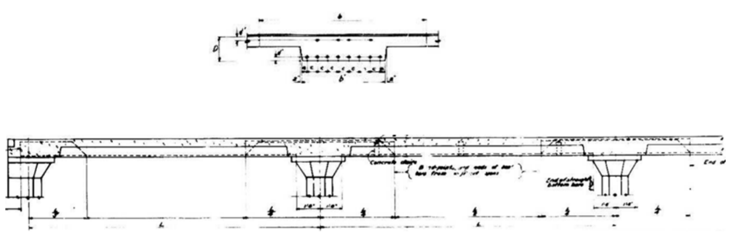


1. Building Description



(Octagonal, Spirally reinf Col's)

1. Building Description



Poll

Which of these attributes is an important predictor of the seismic performance of this building (check as many as you want)?

- ❑ Spirally reinforced columns
- ❑ Shallow slab-column frame system
- ❑ Tall first story
- ❑ Spread footings with no grade beams

2. Loads and Component Strengths

Roof:			
Roofing	5	psf	
6.5" Conc. Slab	81.3	psf	
Conc. Beam	47.0	psf	(Typical 14x50 @ 19.5' Each Way)
Conc. Column	6.7	psf	(Typical 18x18 Octagon @ 19.5' Each Way)
Conc. Wall	30.8	psf	(6.75' Parapet, 8"x154' solid wall, (5)x8"x5' Perforated Wall)
Ceiling	0	psf	
Mech + Plumbing	10	psf	
Misc.	2	psf	
Dead Load	**145**	**psf**	for Column axial
Live Load	**20**	**psf**	
Seismic Weight	**183**	**psf**	

Roof Seismic Weight 3,214 kips

2nd to 5th:			
6.5" Conc. Slab	81	psf	
Conc. Beam	47.0	psf	(Typical 14x50 @ 19.5' Each Way)
Conc. Column	22.1	psf	(Typical 24x24 Octagon @ 19.5' Each Way)
Conc. Wall	17.3	psf	(8"x154' solid wall, (5)x8"x5' Perforated Wall+4' Spandral)
Ceiling	5	psf	
Mech + Plumbing	2	psf	
Partition	15	psf	
Dead Load	**150**	**psf**	for Column axial
Live Load	**50**	**psf**	
Seismic Weight	**190**	**psf**	(3rd, 4th and 5th)
	194	**psf**	(2nd)

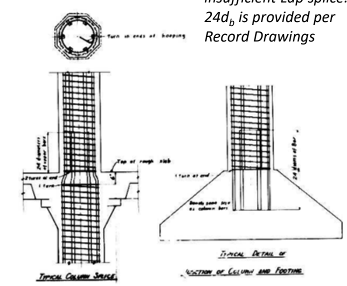
Typical Flr. Seismic Weight 2,834 kips

2. Loads and Component Strengths

General Considerations when Calculating Component Strengths:

- Calculate component flexural/shear strengths based on expected (nominal) material properties, Concrete: f'_{ce} = 3 ksi, and f_{ye} = 50 ksi
- Strength calculations are per ACI 318 with $\phi = 1$
- Consider the effect of expected axial load: $P = P_D + 0.25\ P_L$
- Check for inadequate splices/ rebar development and adjust strengths for undeveloped rebars and lap splices (ASCE 41-17) - - *but not always (such as when calculating column's V_p)*

Take reduction for insufficient Lap splice: $24d_b$ is provided per Record Drawings

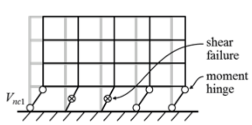


2. Loads and Component Strengths

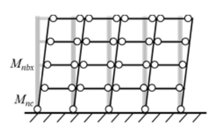
Component Strengths Needed:

>> For calculating *Plastic Mechanism Base-Shear Strength*, the strength of the following components are needed for Mechanisms 1 & 2 (Frame Building):

- First floor columns: flexure and shear strengths *(54 columns)*
- All beams: flexure and shear strengths *(470 beams)*



Mechanism 1



Mechanism 2

>> In addition, when calculating *columns drift capacity*, the *critical* first-floor columns *"capacity-limited shear strengths"* are needed *(54 columns)*

2. Loads and Component Strengths

a. Columns Flexural Strength (ACI 318):

- Obtain columns flexural strength, considering P-M interaction
- Consider insufficient rebar lap splice in moment calculations

(Sample spreadsheet)

ID	Col Info						Results
	b	h	As	A's	Aside	Pg	Mc
	(in)	(in)	(in²)	(in²)	(in²)	(kips)	(k-in)
NS-2-a-2	21	21	1.6	1.6	0.8	142	2,559
NS-2-a-3	23	23	2.4	2.4	1.2	218	4,096
NS-2-b-1	23	23	2.4	2.4	1.2	218	4,096
NS-2-b-4	23	23	5.3	5.3	2.7	334	6,830

2. Loads and Component Strengths

b. Columns Shear Strength (ASCE-41-17):

$$V_n = k\left(\frac{A_v f_{ye} d}{s} + \lambda\left(\frac{6\sqrt{f'_{ce}}}{l_{inf}/d}\sqrt{1+\frac{P_g}{6\sqrt{f'_{ce}}A_g}}\right)0.8A_g\right)$$

k = 1
s = Spacing of shear ties
Av = Area of shear ties
d = effective depth of column section,0.8hc
fye = 41.25 ksi
λ = 1 (normal weight 1, light weight concrete 0.75)
f'ce = 3 ksi
linf = half of column clear height at typical floor, 0.6h1 at first floor
Pg = expected gravity axial load calculated above in Section 1.6
Ag = gross area of column section

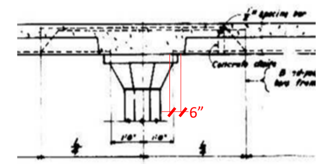
(Sample spreadsheet)

Story	Location	s	Av	d	linf	Pg	Ag	Vn
		(in)	(in^2)	(in)	(in)	(kips)	(in^2)	(kips)
1st	2/b	2.75	0.153	20.8	120.3	333.6	530.9	117.6
1st	3/a	2.75	0.153	20.8	120.3	218.5	530.9	110.4
1st	9/b	2.75	0.153	19.2	120.3	181.2	452.4	97.8
1st	1/a	2.75	0.153	19.2	120.3	142.3	452.4	95.1
1st	1/g	2.75	0.153	19.2	120.3	123.7	452.4	93.8
1st	9/g	2.75	0.153	19.2	120.3	105.1	452.4	92.4

2. Loads and Component Strengths

c. Beams Flexure and Shear Strength (ACI 318):

- Calculate beams flexure and shear strengths using ACI 318
- Take reduction for any discontinuous rebars or deficient lap splice. In this example, bottom reinforcement of interior beams extends only 6” into column-slab joints



2. Loads and Component Strengths

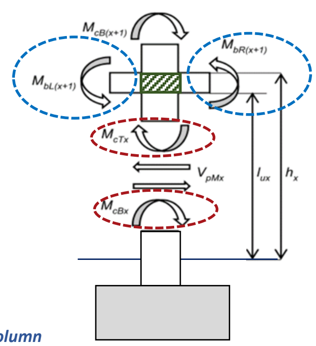
d. Columns Capacity-Limited Shear Strength:

$V_{pc} = min(V_{pM}, V_n)$ $\quad V_{pM} = \frac{M_{cT} + M_{cB}}{l_u}$

M_{cT} and M_{cB} : Lesser of the

1. Flexural strength of the column section
2. Flexural strength controlled by the beams or slabs (including shear-limiting flexural capacity of beams)
3. Moment transfer strength of the slab-column connection based on punching shear

As an example, take Frame on Gridline 2 - interior column



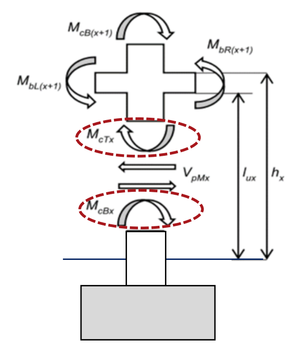
2. Loads and Component Strengths

d. Columns Capacity-Limited Shear Strength:

1. Calculate flexural strength of the column “section”:

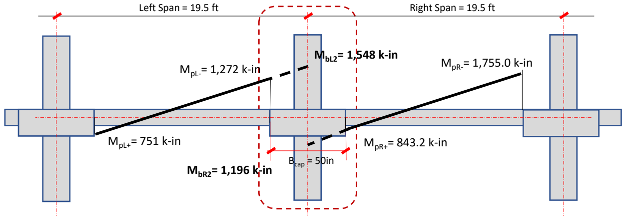
Top of Column Section Flexural Strength:
M_{cT1} = 6,830 *k-in*

Bottom of Column Flexural Strength:
M_{cB1} = 3,415 *k-in (assuming 50% strength at base)*



2. Loads and Component Strengths

2. Check if the flexural strength of the column top is controlled by the flexural strength of the slab-beams (including shear-limiting flexural capacity of beams);



a. Calculate plastic moments of slab-beams at col. centerline:

M_{bL2} = ***1,548*** *k-in*

M_{bR2} = ***1,196*** *k-in*

b. Shear strength check (left beam):

V_{pML} = (1,272+751) / 184 = 11 kips --- Flexural

< V_{nL} = 65.7 kips --- Shear

Thus, Flexural Governs

c. Obtain beam-controlled flexural strength at top of the column:

$M_{cT1} = [M_{bL2}+M_{bR2}]\ (h_1) / (h_1+h_2) =$ ***1,565*** *k-in*

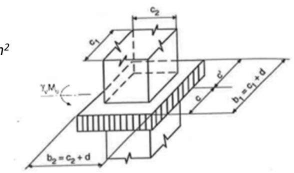
2. Loads and Component Strengths

3. Check Slab-Column Connection Moment Transfer Capacity

Critical Section Geometry: *d = 11 in* $c_1=c_2=50$ *in,* $b_1=b_2=61$ *in A = 2,675 in*^{2}

Ratio of shear and flexural transfer: $\gamma_f = \frac{1}{1+(2/3)\sqrt{b_1/b_2}}$ $\gamma_f = 1/(1+2/3) = 0.60$; $\gamma_v = 1 - \gamma_f = 0.40$

Modulus of Critical Section (Polar Moment of Inertia): $J/c = J/c' = \frac{b_1 d(b_1+3b_2)+d^3}{3} = 54{,}812\ in^3$



Punching stress capacity, reduced by gravity load: v_c = 208 psi (ACI 318) ; $v_g = V_g/A$ = 71.6 kip/2,675 in^2 = 27 psi ; v_c-v_g = 181 psi

Slab-Column connection moment transfer capacity associated with punching shear: $(v_c-v_g)\ (J/c) / \gamma_v$ = 181 x 54,812 / 0.4 = **24,850** k-in *(doesn't govern)*

2. Loads and Component Strengths

d. Columns Capacity-Limited Shear Strength:

Thus, Top of Column Flexural Strength:

M_{cT1} = **1,565** *k-in*

Bottom of Column Flexural Strength:

M_{cB1} = **3,415** *k-in (assuming 50% strength at base)*

Column plastic shear strength based on flexural strength:

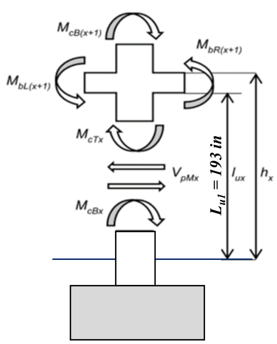
V_{pM1} = (1,565 + 3,415) / 193 = 25.8 kips

Column section shear strength:

V_n = 118 kips

$V_{pc} = min(V_{pMx}, V_n)$

V_{pc} = **25.8** *kips --- Flexural Controlled*

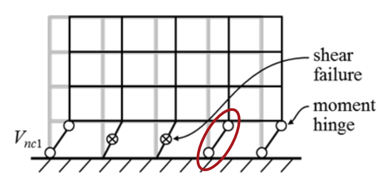


3. Plastic Mechanism Base-Shear Strength

Mechanism #1 Assumes building strength controlled by the structural elements in the first story

For each column, calculate shear strength V_{nc1} and the shear associated with development of the column flexural strength, and take the minimum, that is:

$$V_{nc1} = \min\left[V_{nc}, \sum M_{nc}/l_u\right]$$



For a typical interior column:

Column flexural strength at top: M_{ncT} = 6,830 k-in

Column flexural strength at bottom: M_{ncB} = 3,415 k-in (assuming 50% fixity at base)

Column Clear Height: l_u = 193 in

Column Shear if *flexural controls*:

$\sum M_{nc}/l_u$ = (6,830 + 3,415) / 193 = **53** kips

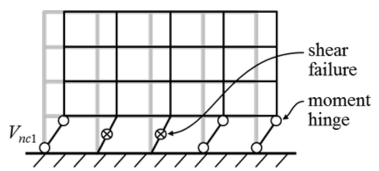
Column Shear Capacity: V_{nc} = **118** kips > $\sum M_{nc}/l_u$

V_{nc1} = **53** kips - - >> Flexural Controls

$\sum V_{nc1}$ = 276 kips –– Total for Frame on Gridline 2

3. Plastic Mechanism Base-Shear Strength

Mechanism #1 Assumes building strength controlled by the structural elements in the first story



There are total of 9 Frames:

Frame on Gridline 1:

$\sum V_{nc1}$ = 167 kips

Frames on Gridlines 2 - 8:

(7) x $\sum V_{nc1}$ = (7) x 276 kips

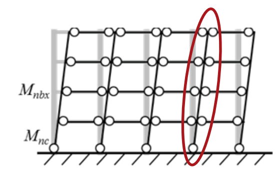
Frame on Gridline 9:

$\sum V_{nc1}$ = 370 kips

V_{P1} = 167 + 276 x7 + 370 = **2,470 kips**

3. Plastic Mechanism Base-Shear Strength

Mechanism #2 Assumes that columns have sufficient strength to force yielding thru building height



$$V_{p1} = \frac{\sum M_{nc1} + \sum M_{nbx}}{h_{eff}}$$

where $h_{eff} = 0.7 h_n$

For an interior column of the frame on Gridline 2:

2nd floor and above:

Summation of beams flexural strength, ΣM_{nb} = *2,744 k-in*

Column base flexural strength, M_{nc1} = *3,415 k-in* (assuming 50% fixity)

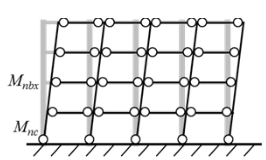
V_{p1} = (3,415+2,744 x 5) / 590

= 29 kips @ an interior column in Frame 2

V_{p1} = 157 kips - Total for Frame on Gridline 2

3. Plastic Mechanism Base-Shear Strength

Mechanism #2 Assumes that columns have sufficient strength to force yielding thru building height



There are total of 9 Frames:

Frame on Gridline 1:

$\sum V_{p1}$ = 124 kips

Frames on Gridlines 2 - 8:

(7) x $\sum V_{p1}$ = (7) x 157 kips

Frame on Gridline 9:

$\sum V_{p1}$ = 201 kips

V_{P1} = 124 + 157 x7 + 201 = **1,424 kips**

3. Plastic Mechanism Base-Shear Strength

Thus, Plastic Mechanism 2 governs:

- Critical Story = 1st Story
- Effective Yield Strength V_y = **1,424** kips
- Building Total Seismic Weight W = 14,610 kips

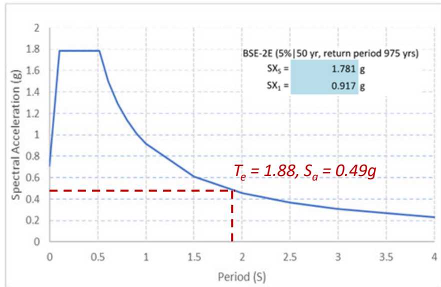
$V_y/W = \mathbf{9.7\%}$

4. Global Seismic Drift Demand

- Calculate the Effective Fundamental Period for the "frame" building:

$$T_e = 0.07(h_n)^{0.5}\left(\frac{V_y}{W}\right)^{-0.5}$$
$$= 0.07(70.25')^{0.5}(0.097)^{-0.5}$$
$$= \mathbf{1.88}\ \text{sec}$$

- Develop the Acceleration Response Spectrum for the BSE-2E Earthquake



29

4. Global Seismic Drift Demand

Check for Early-out - - Calculate Global Demand-to-Capacity Ratio, $\mu_{strength}$

$$\mu_{strength} = \frac{S_a}{V_y / W} C_m \qquad (5\text{-}23)$$

where S_a is the spectral acceleration at the effective fundamental period, T_e, V_y is the effective yield strength, and C_m is the effective mass factor determined in accordance with ASCE/SEI 41-17, as provided in Table 5-1.

Table 5-3 Values for Effective Mass Factor, C_m

No. of stories	Frame System	Wall or Frame-Wall System	Pier-Spandrel System	Infill Wall System
1-2	1.0	1.0	1.0	1.0
≥ 3	0.9	0.8	0.8	1.0

Note: C_m shall be taken as 1.0 if the fundamental period, T_e, in the direction under consideration is greater than 1.0 sec.

30

4. Global Seismic Drift Demand

Check for Early-out - - Calculate Global Demand-to-Capacity Ratio, $\mu_{strength}$

$$\mu_{strength} = \frac{S_a}{V_y/W} C_m$$
$$= 0.49(1.0)/0.097$$
$$= 5.0$$

No early-out, but…!

Classification	Structural System	$\mu_{strength}$
Lower seismic risk	Frames with shear-critical columns ($V_p/V_n > 0.6$)	≤ 0.75
	All other cases	≤ 1.5
Exceptionally high seismic risk	Frames with shear-critical columns ($V_p/V_n > 1.5$)	> 2.0
	Frames without shear critical columns ($V_p/V_n \le 0.6$)	> 5.5
	Some discontinuous wall-on-column conditions	Any
	Some discontinuous wall-on-girder conditions	Any
	Some pounding conditions	Any

31

4. Global Seismic Drift Demand

Calculate Global Seismic Drift Demand

$$\delta_{eff} = C_1 C_2 S_a \frac{T_e^2}{4\pi^2} g$$

Equivalent SDOF displacement

SDOF spectral displacement

Coefficient to amplify short-period drift (from ASCE 41)

$$C_1 = 1 + \frac{\mu_{strength} - 1}{a T_e^2}$$

Coefficient to amplify drift due to degradation (from ASCE 41)

$$C_2 = 1 + \frac{1}{800}\left(\frac{\mu_{strength} - 1}{T_e}\right)^2$$

(All from ASCE 41)

$C_1 = 1.0\ (T_e > 1.0)$

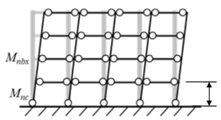
$C_2 = 1.0\ (T_e > 0.7)$

$$\delta_{eff} = (1.0)(1.0)(0.49)\frac{1.9^2}{4\pi^2}(386)$$
$$= \textbf{16.9 in}$$

32

5. Drift Demand on Critical Story

a. Critical Story Drift Demand Adjustment – α



$$\delta_x = \alpha_x h_{sx}\left(\frac{\delta_{eff}}{h_{eff}}\right) \le \delta_{eff}$$

α_x = 1.5, h_{sx} = 17.25', h_{eff} = 0.7 x 70.25' = 49.2'

Therefore, $\delta_1 = 0.53\delta_{eff}$ = ***8.9 in***

In terms of drift ratio, $\frac{\delta_1}{h_{s1}} = 0.04$

Table 6-1 Values for Coefficient α

No. of Stories in the Building	Yield Mechanism	Values of α[1] Critical Stories	Values of α[1] Other Stories
1	(any)	1.0	(n/a)
2	1, 3	2.0	0.5
	2, 4	1.5	1.0
3-6	1, 3	2.0	$1-0.5\frac{x-2}{n-2}$
	2, 4	1.5	1.0
7-8	1, 3	*Linearly interpolate between the values for 6 and 9 stories*	
	2, 4	*Linearly interpolate between the values for 6 and 9 stories*	
= 9	1, 3	2.5	1.5
	2, 4	1.5	1.0

[1] x is the story under consideration; n is the total number of stories.

5. Drift Demand on Critical Story

b. Critical Story Drift Demand Adjustment – P-Δ

$$\delta_{x1} = \delta_x\left[\frac{1}{1-\frac{W_x\delta_x}{V_{px}h_x}}\right]$$

Amplified story drift

Plastic mechanism shear strength at story x

Gravity load above level x

Height from base of building to level x

<u>For the critical 1st Story:</u>

W_1 = 14,610 kips

δ_1 = 8.9 in (already amplified by 1.5)

V_{p1} = 1,424 kips

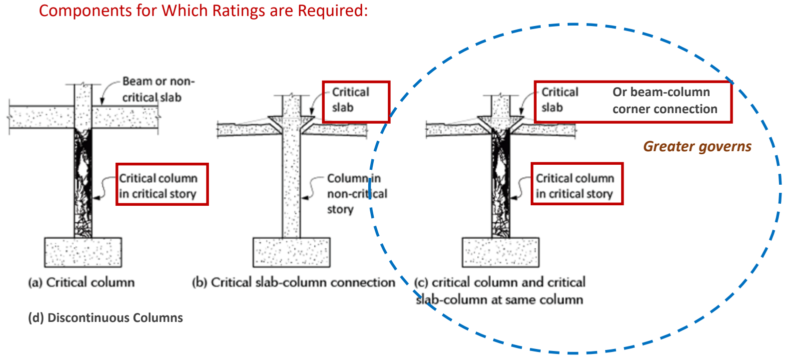
h_1 = 17.25 feet

δ_{x1} = 8.9 in x (1.79) ***= 15.9 in***

In terms of drift ratio, now $\frac{\delta_1}{h_{s1}} = 0.08$

6. Drift Demand on Critical Components

Components for Which Ratings are Required:



(a) Critical column

(b) Critical slab-column connection

(c) critical column and critical slab-column at same column

(d) Discontinuous Columns

6. Drift Demand on Critical Components

Calculate Component Drift Factors. *The Drift Factor, γ, defines the portion of the story drift demand attributable to component deformations:*

\>> Component Drift Demand = γ x Story Drift Demand

For the <u>Critical Columns</u>: $\frac{\sum M_c}{\sum M_b} = 3.72$ Thus, γ = 0.30 per the table below

Ratio of Column Strengths to Beam Strengths[2] $\sum M_c/\sum M_b$	Column Drift Factor γ
≤ 0.6	0.85
1	0.70
≥ 2.4	0.30

For the <u>Critical Slab-Column</u> and <u>Beam-Column Corner Connections</u>: γ = 1.0

6. Drift Demand on Critical Components

Calculate Component Drift Factors. *The Drift Factor, γ, defines the portion of the story drift demand attributable to component deformations:*

>> Component Drift Demand = γ x Story Drift Demand

				Demand				
				Story Drift	γ–"Col"	γ–"Conn"	Δ_D-"Col"	Δ_D-"Conn"
Story	Frame Gridline	Gridline	Type	δ_{col}	γ	γ	Δ_D	Δ_D
				(in)			(in)	(in)
1st Story	2	A	Slab-Col Frame	15.85	0.30	1.00	4.76	15.85
1st Story	2	B	Slab-Col Frame	15.85	0.30	1.00	4.76	15.85
1st Story	2	C	Slab-Col Frame	15.85	0.30	1.00	4.76	15.85
1st Story	2	D	Slab-Col Frame	15.85	0.30	1.00	4.76	15.85
1st Story	2	F	Slab-Col Frame	15.85	0.30	1.00	4.76	15.85
1st Story	2	G	Slab-Col Frame	15.85	0.30	1.00	4.76	15.85

7. Drift Capacity of Critical Components

a. Drift Capacity of Critical Columns

$$\Delta_c = l_u(\theta_c + 0.01)$$

where:

l_u = clear height of the column

θ_c = column plastic rotation capacity

V_P = Column capacity-limited shear strength

Flexure-Critical Columns ($V_p/V_n \le 0.6$, $\rho_t > 0.002$, and $s/d < 0.5$)	
For $\left(\frac{P}{A_g f'_{ce}}\right) \ge 0.1$	$\theta_c = 1.15\left[11.4\rho_t + 0.034 - \left(\frac{P}{A_g f'_{ce}}\right)(14\rho_t + 0.036)\right] \ge 0.0$
For $\left(\frac{P}{A_g f'_{ce}}\right) < 0.1$	$\theta_c = 1.15[10\rho_t + 0.03] \ge 0.0$
Flexure-Shear and Shear-Critical Columns (i.e., Columns not classified as Flexure-Critical Columns)	
For $\left(\frac{P}{A_g f'_{ce}}\right) \le 0.5$	$\theta_c = \frac{0.65}{5 + \frac{P}{0.8 A_g f'_{ce}} \frac{1}{\rho_t} \frac{f'_{ce}}{f_{ye}}} - 0.01 \ge \theta_{c,min}$ $P/A_g f'_{ce}$ should not be taken smaller than 0.1
θ_c should be reduced linearly for $\left(\frac{P}{A_g f'_{ce}}\right) > 0.5$ from its value at $\left(\frac{P}{A_g f'_{ce}}\right) = 0.5$ to zero at $\left(\frac{P}{A_g f'_{ce}}\right) = 0.7$	
$\theta_{c,min} = 0.06 - 0.06\left(\frac{P}{A_g f'_{ce}}\right) + 1.3\rho_t - 0.037\left(\frac{V_p}{V_n}\right) \ge 0.0$ $P/A_g f'_{ce}$ should not be taken smaller than 0.1	

7. Drift Capacity of Critical Components

a. Drift Capacity of Critical Columns

Column capacity-limited shear strength:

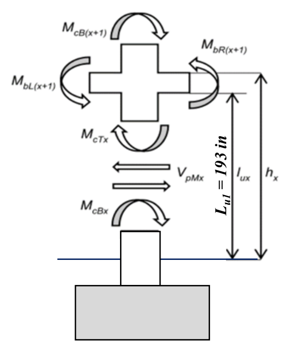
Column section shear strength:

V_n = 118 kips

V_p = 25.8 kips

Shear Ratio: (plastic shear vs. shear capacity)

V_p/V_n = 0.22



7. Drift Capacity of Critical Components

a. Drift Capacity of Critical Columns

Shear Ratio: (plastic shear vs. shear capacity)

$V_p/V_n = 0.22 < 0.6$

Axial Load Ratio:

$P_g/(A_g f'_{ce}) = 0.209 > 0.1$

Transverse Reinf. Ratio:

$r_t = A_v/(b_w s) = 0.0025 > 0.002$

Transverse Reinf. Spacing:

$s/d < 0.5$

Flexure-Critical Columns ($V_p/V_n \le 0.6$, $\rho_t > 0.002$, and $s/d < 0.5$)	
For $\left(\frac{P}{A_g f'_{ce}}\right) \ge 0.1$	$\theta_c = 1.15\left[11.4\rho_t + 0.034 - \left(\frac{P}{A_g f'_{ce}}\right)(14\rho_t + 0.036)\right] \ge 0.0$
For $\left(\frac{P}{A_g f'_{ce}}\right) < 0.1$	$\theta_c = 1.15[10\rho_t + 0.03] \ge 0.0$

θ_c = **0.055**

L_u = 193 in

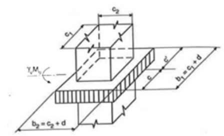
$$\Delta_c = l_u(\theta_c + 0.01)$$

Δ_c = 193 (0.061 +0.01) = **12.6** in

7. Drift Capacity of Critical Components

b. Drift Capacity of Critical Slab-Column Connections (Based on Punching Shear)

Gravity Shear Ratio (a) V_g/V_c	Drift Capacity, Δ_c
≤ 0.1	$0.045h_{sx}$
≥ 0.6	$0.01h_{sx}$



$v_g = V_g / A = 71.6 \text{ kip} / 2{,}675 \text{ in}^2 = 27 \text{ psi}$

$v_c = \left(2 + \frac{\alpha_s d}{b_0}\right)\sqrt{f'_c}\, b_0 d = 208 \text{ psi}$ (ACI 318)

$v_g / v_c = 0.129$ At first story, $h_{sx} = 194$ in

$\Delta_c = 0.043\, h_{s1} =$ ***8.3*** *in*

$d = 11$ in; $c_1 = 50$ in, $c_2 = 50$ in
$b_1 = 61$ in, $b_2 = 61$ in
$A = 2{,}675$ in^2

7. Drift Capacity of Critical Components

c. Drift Capacity of Critical Beam-Column Corner Connections

$$\Delta_c = \left(0.1 - 0.33\frac{P}{A_g f'_{ce}}\right) h_{sx}$$

Largest corner column axial load ratio is:

P = 158 kips
$A_g f_{ce}' =$ 1,357 kips
$P/(A_g f_{ce}') = 0.116$

$\Delta_c = (0.1 - 0.33 \times 0.116)\, h_{sx} = 0.062\, h_{sx}$
At first story, $h_{sx} = 194$ in
$\Delta_c =$ ***12.0*** in

8. Critical Columns Rating

Drift Demand/Capacity Ratios for Critical Columns and Slab-Column Connections –
(Showing Gridline 2 only)

				Demand					Capacity		D/C Ratio
				Story Drift	γ–"Col"	γ–"Conn"	Δ_D-"Col"	Δ_D-"Conn"	Δ_c-"Col"	Δ_c-"Conn"	Δ_D / Δ_c
Story	Frame Gridline	Gridline	Type	δ_{col}	γ	γ	Δ_D	Δ_D	Δ_c	Δ_c	DCR
				(in)			(in)	(in)	(in)	(in)	
1st Story	2	A	Slab-Col Frame	15.85	0.30	1.00	4.76	15.85	13.72	8.52	1.86
1st Story	2	B	Slab-Col Frame	15.85	0.30	1.00	4.76	15.85	12.57	8.30	1.91
1st Story	2	C	Slab-Col Frame	15.85	0.30	1.00	4.76	15.85	12.57	8.30	1.91
1st Story	2	D	Slab-Col Frame	15.85	0.30	1.00	4.76	15.85	12.57	8.30	1.91
1st Story	2	F	Slab-Col Frame	15.85	0.30	1.00	4.76	15.85	12.57	8.30	1.91
1st Story	2	G	Slab-Col Frame	15.85	0.30	1.00	4.76	15.85	13.72	8.52	1.86

8. Critical Columns Rating

Every column (location) at the critical story is assigned a Column Rating, CR_i, based on the highest Δ_D/Δ_C rating for any critical component at that location

Drift Demand to Drift Capacity Ratio Δ_D/Δ_C	Column Rating *CR*
$\Delta_D/\Delta_C \leq 0.25$	0.0
$0.4 \geq \Delta_D/\Delta_C > 0.25$	0.1
$0.5 \geq \Delta_D/\Delta_C > 0.4$	0.2
$0.7 \geq \Delta_D/\Delta_C > 0.5$	0.3
$0.9 \geq \Delta_D/\Delta_C > 0.7$	0.4
$1.1 \geq \Delta_D/\Delta_C > 0.9$	0.5
$1.4 \geq \Delta_D/\Delta_C > 1.1$	0.6
$1.8 \geq \Delta_D/\Delta_C > 1.4$	0.7
$2.5 \geq \Delta_D/\Delta_C > 1.8$	0.8
$3.0 \geq \Delta_D/\Delta_C > 2.5$	0.9
$\Delta_D/\Delta_C > 3.0$	0.93

8. Critical Columns Rating

Columns Rating –
(Showing Gridline 2 only)

				Demand					Capacity		D/C Ratio	
				Story Drift	γ–"Col"	γ–"Conn"	Δ_D-"Col"	Δ_D-"Conn"	Δ_c-"Col"	Δ_c-"Conn"	Δ_D / Δ_c	Col Rating
Story	Frame Gridline	Gridline	Type	δ_{col}	γ	γ	Δ_D	Δ_D	Δ_c	Δ_c	DCR	CR_i
				(in)			(in)	(in)	(in)	(in)		
1st Story	2	A	Slab-Col Frame	15.85	0.30	1.00	4.76	15.85	13.72	8.52	1.86	**0.8**
1st Story	2	B	Slab-Col Frame	15.85	0.30	1.00	4.76	15.85	12.57	8.30	1.91	**0.8**
1st Story	2	C	Slab-Col Frame	15.85	0.30	1.00	4.76	15.85	12.57	8.30	1.91	**0.8**
1st Story	2	D	Slab-Col Frame	15.85	0.30	1.00	4.76	15.85	12.57	8.30	1.91	**0.8**
1st Story	2	F	Slab-Col Frame	15.85	0.30	1.00	4.76	15.85	12.57	8.30	1.91	**0.8**
1st Story	2	G	Slab-Col Frame	15.85	0.30	1.00	4.76	15.85	13.72	8.52	1.86	**0.8**

9. Story Rating

$$R_{avg} = \sum_{i=1}^{ncol} f_{col,i} CR_i$$

R_{avg} = The weighted mean column rating for all columns in the story, weighted by the gravity load taken by each column

$f_{col,i}$ = Fraction of gravity loads supported by column *i* in a story. $\sum_{i=1}^{ncol} f_{col,i} = 1$ in each story

R_{avg} = 0.805

			Δ_D / Δ_c	Col Rating	Gravity Load	Trib. Ratio	
Story	Frame Gridline	Gridline	DCR	CR_i	P_g	f_{col}	CRi x f_{col}
					(kips)		
1st Story	2	A	1.86	**0.8**	218	0.014	0.011
1st Story	2	B	1.91	**0.8**	334	0.021	0.017
1st Story	2	C	1.91	**0.8**	334	0.021	0.017
1st Story	2	D	1.91	**0.8**	334	0.021	0.017
1st Story	2	F	1.91	**0.8**	334	0.021	0.017
1st Story	2	G	1.86	**0.8**	218	0.014	0.011
1st Story	3	A	1.86	**0.8**	218	0.014	0.011
1st Story	3	B	1.91	**0.8**	334	0.021	0.017
1st Story	3	C	1.91	**0.8**	334	0.021	0.017
1st Story	3	D	1.91	**0.8**	334	0.021	0.017
1st Story	3	F	1.91	**0.8**	334	0.021	0.017
1st Story	3	G	1.86	**0.8**	218	0.014	0.011
1st Story	9	A	3.96	**0.93**	290	0.018	0.017
1st Story	9	B	1.91	**0.8**	448	0.028	0.022
1st Story	9	C	1.91	**0.8**	448	0.028	0.022
1st Story	9	D	1.91	**0.8**	448	0.028	0.022
1st Story	9	F	1.91	**0.8**	448	0.028	0.022
1st Story	9	G	3.96	**0.93**	290	0.018	0.017
			Mean		15,929	1.00	0.805
			Std Dev	0.02			
			R_{avg}	0.80			
			R_{adj}	0.80			

9. Story Rating

Adjustment based on coefficient of variation:

$$R_{adj} = R_{avg} + 0.625 R_{avg}(COV - 0.4)$$

COV = the standard deviation of all the *column ratings* at a story divided by the weighted mean column rating at that story

$R_{avg} < R_{adj} < 1.25\, R_{avg}$

$>> R_{adj} = 0.8$

Story Rating:

$$SR = 1.5 R_{adj} - 0.1$$

SR = 1.5 (0.80) - 0.1 = 1.10 (0.1 < SR < 0.9)

>> SR = 0.9

			Δ_D / Δ_c	Col Rating	Gravity Load	Trib. Ratio	
Story	Frame Gridline	Gridline	DCR	CR_i	P_g	f_{col}	CRi x f_{col}
					(kips)		
1st Story	2	A	1.86	**0.8**	218	0.014	0.011
1st Story	2	B	1.91	**0.8**	334	0.021	0.017
1st Story	2	C	1.91	**0.8**	334	0.021	0.017
1st Story	2	D	1.91	**0.8**	334	0.021	0.017
1st Story	2	F	1.91	**0.8**	334	0.021	0.017
1st Story	2	G	1.86	**0.8**	218	0.014	0.011
1st Strory	3	A	1.86	**0.8**	218	0.014	0.011
1st Strory	3	B	1.91	**0.8**	334	0.021	0.017
1st Strory	3	C	1.91	**0.8**	334	0.021	0.017
1st Strory	3	D	1.91	**0.8**	334	0.021	0.017
1st Strory	3	F	1.91	**0.8**	334	0.021	0.017
1st Strory	3	G	1.86	**0.8**	218	0.014	0.011
1st Strory	9	A	3.96	**0.93**	290	0.018	0.017
1st Strory	9	B	1.91	**0.8**	448	0.028	0.022
1st Strory	9	C	1.91	**0.8**	448	0.028	0.022
1st Strory	9	D	1.91	**0.8**	448	0.028	0.022
1st Strory	9	F	1.91	**0.8**	448	0.028	0.022
1st Strory	9	G	3.96	**0.93**	290	0.018	0.017
			Mean	0.80	15,929	1.00	0.805
			Std Dev	0.02			
			R_{avg}	0.80			
			R_{adj}	0.80			

10. Building Rating

The building rating, *BR*, is taken as the maximum story rating, *SR*, determined in either direction, for critical stories over the height of a building.

BR = 0.9

Poll

Did you predict this building to be so seismically vulnerable?

- ❑ Yes
- ❑ No
- ❑ I really had no idea…

Questions?

FEMA P-2018:
Policy Implications

Bill Holmes, Structural Engineer, Rutherford + Chekene

FEMA

nehrp

1

1.4 Policy Implications

- Ratings (ranking) are intended to give significance of risk of collapse
- Could be used by jurisdiction or by owner of large inventory ,of buildings
- An example program is included in Section 1.4 and is summarized below (I believe San Francisco has already started with some steps)
- All time periods are local policy issues. Examples are **included** here:

  Using sidewalk surveys, assessors' files, or other available jurisdictional records, develop a preliminary inventory of older concrete buildings (i.e., buildings not conforming to the 1976 Uniform Building Code, or not meeting other locally accepted evaluation or retrofit standards).

FEMA FEMA P-2018: Seismic Evaluation of Older Concrete Buildings for Collapse Potential 2 nehrp

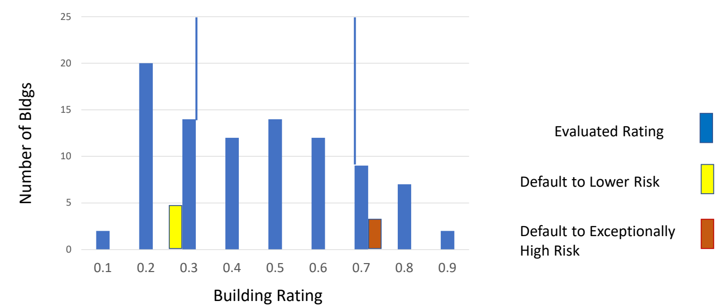
2

Example Program from Section 1.4

- Within the first year of a program, require building owners in the preliminary inventory to submit a simple building data collection form, with input from an engineer or architect, to confirm the building status, and possibly identify additional risk factors.
- Develop a refined inventory of older concrete buildings based on information contained in building data collection forms.
- Within approximately three years, require building owners in the refined building inventory to evaluate and classify their buildings using this methodology.

FEMA FEMA P-2018: Seismic Evaluation of Older Concrete Buildings for Collapse Potential 3 nehrp

3



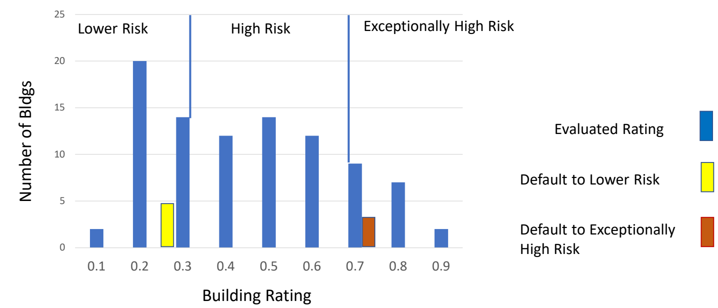
Example Inventory

FEMA FEMA P-2018: Seismic Evaluation of Older Concrete Buildings for Collapse Potential 4 nehrp

4

Example Program from Section 1.4

- Develop a prioritized inventory of older concrete buildings based on information obtained from the building evaluations.
  - Use three categories of
    - Exceptionally High Risk
    - High Risk
    - Lower Risk
  - OR, for finer separation, use individual building ratings from 0.1 to 0.9



Example Inventory

Example Program from Section 1.4

- Within approximately five years, require mitigation of the risk associated with exceptionally high seismic risk buildings through more detailed evaluation or retrofit, if needed, using ASCE/SEI 41 or other locally accepted evaluation or retrofit standards.
- Over a longer period of time, require mitigation of the risk associated with high seismic risk buildings and lower seismic risk buildings through more detailed evaluation or retrofit, if needed.

Example Program from Section 1.4

It is expected that the state of knowledge in ASCE/SEI 41 will continue to evolve over time, and that many buildings in lower seismic risk categories could be deemed to be acceptably safe in the future. It is also possible that additional information gained from the use of this methodology over time will demonstrate that the criteria are sufficiently reliable for identifying buildings that are acceptably safe without further evaluation (at least in the case of lower seismic risk buildings).