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

Bill Holmes, Rutherford + Chekene

Abbie Liel, University of Colorado, Boulder

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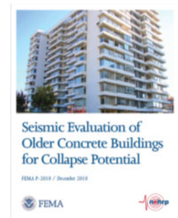
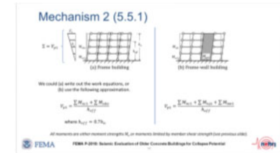
1

Webinar Handouts



FEMA P-2018 Report

Guidance for Implementation



Webinar slides

Example application

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2

FEMA P-2018: Introduction/Overview

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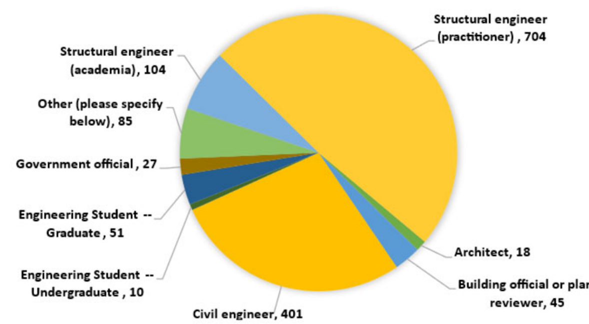
3

Almost 1500 registered



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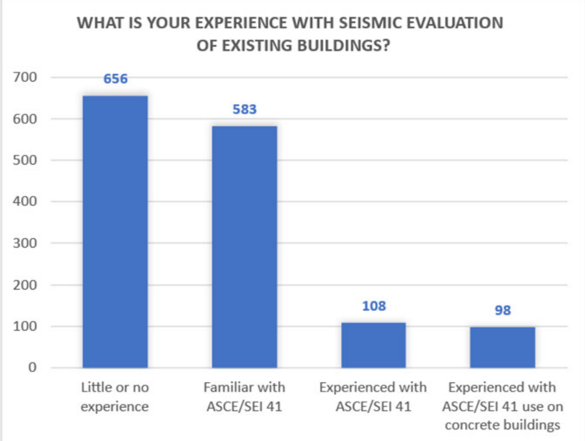
4



Agenda of Seminar

- Introduction/Overview — Bill Holmes
- Demand as used in the methodology — Bill Holmes
- Capacity as used in the methodology — Abbie Liel
- Typical Chapter for Building Types and Example — Abbie Liel
- Wrap up — Bill Holmes

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?
- Overview of methodology

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)

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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 (could be called 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.

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9

Epitome of Exceptionally High-Risk Building

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10

During development of FEMA P-2018, Method to measure collapse risk evolved

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

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 (160 hr +-)

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11

Some things to we had to consider…

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12

Column failure leading to axial failure

Izmit, Turkey, 1999

Photo courtesy of Jack Moehle

13

Column failure leading to implosion

Northridge, 1994

Photo courtesy of Jack Moehle

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

14

Joint failures

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

Northridge, 1994

15

Wall failure leading to overturning

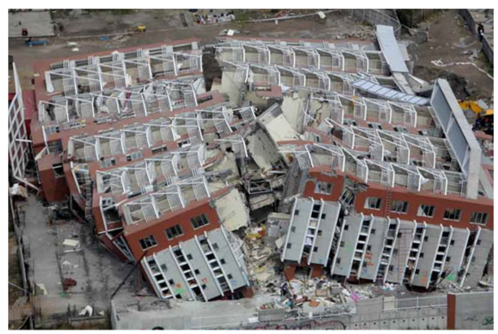

Photo courtesy of Jack Moehle

16

Wall failure leading to inward collapse

How are the ratings done?

- Estimate story drift demands-from the selected ground motion--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
- Capacities based on probability of loss of gravity carrying ability based on available tests
- 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."

How is FEMA P-2018 different than ASCE/SEI 41?

- ASCE 41 is a national standard for seismic evaluation and retrofit and covers essentially all materials and building types.
  - ❑ **P-2018 targets only older (pre 1976 UBC) concrete buildings.**
- The analytical methods of ASCE 41 are component based, measuring the seismic demand and capacity of individual structural elements such as beams, columns, walls, etc.
  - ❑ **P-2018 produces results on a global basis, measuring the risk of story collapse.**
- ASCE 41 can measure several damage states of individual members, including Immediate Occupancy, Life Safety, and Collapse Prevention.
  - ❑ **P 2018 is focused on the danger from collapse of an older concrete building**
- In ASCE 41, for many buildings, nonlinear analysis is suggested-or necessary to obtain realistic and non-conservative results.
  - ❑ **Nonlinear concepts are built into P 2018 and the methodology is intended to get more consistent results in less time.**

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 (α_x factors)
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 (gravity load)
*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?

- Consider not only the lateral system (many don't have one)
- But also the gravity system

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

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

25

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.

26

Chapter 5: the hub of the methodology

27

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**

Identify structure-type
Important for structure period and story drift determination

28

Chapter 5: the hub of the methodology

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

Story collapse calculations in
Chapter 6 (Frames)
Chapter 7 (Frame Walls)
Chapter 8 (Bearing Walls)
Chapter 9 (Infill Frames)

Typical Flow in 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

FEMA P-2018:
Demands, specifically drift demands from
Mechanism Analysis

Bill Holmes, Structural Engineer, Rutherford + Chekene

(Slides by Jack Moehle, University of California, Berkeley)

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33

Chapter 5: the hub of the methodology

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

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34

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34

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 (P 2018 method)
2) Nonlinear static analysis (if results available)

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35

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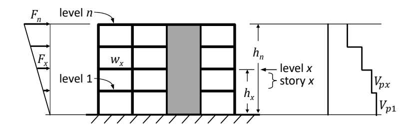
35

Definitions (5.5.1)



(a) Lateral forces (b) Building elevation (c) Story shears

$$F_x = C_{vx} V_{p1}, \text{ where } C_{vx} = \frac{w_x h_x}{\sum_{i=1}^{n} w_i h_i}$$

(this is simplified from ASCE 41)

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

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36

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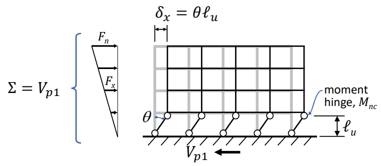
36

Mechanism 1 (5.5.1)



Bare frame

Using the principal of virtual displacements

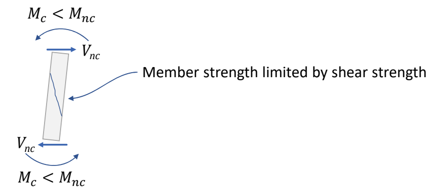
$$W_{ext} = W_{int}$$

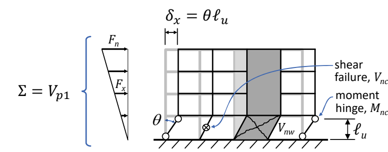
$$V_{p1}\delta_x = \sum M_{nc}\theta$$

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

37

Mechanism 1 (5.5.1)





Frame-wall

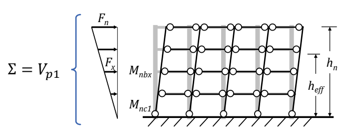
$$W_{ext} = W_{int}$$

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

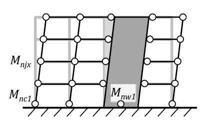
$$V_{p1} = \frac{1}{\ell_u}\sum M_{nc} + \sum V_{nc} + \sum V_{nw}$$

38

Mechanism 2 (5.5.1)



(a) Frame building



(b) Frame-wall building

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 $h_{eff} = 0.7h_n$

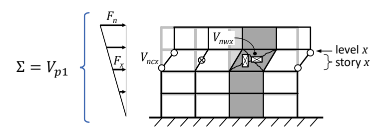
$$V_{p1} = \frac{\sum M_{nc1} + \sum M_{njx} + \sum M_{nw1}}{h_{eff}}$$

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

39

Mechanism 3 (5.5.1)

req'd for vertically irregular framing

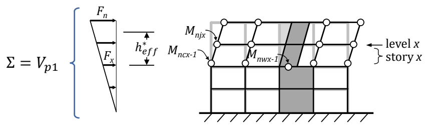


Vertically irregular structure

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: $V_{p1} = V_{px}/\Sigma_{i=x}^{n} C_{vi}$

40

Mechanism 4 (5.5.1)
(req'd for vertically irregular framing)

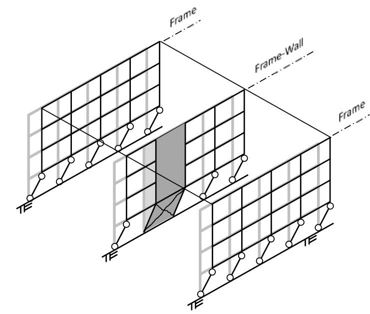


(a) Mechanism 4

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: $V_{p1} = V_{px} / \sum_{i=x}^{n} C_{vi}$

41

Mechanisms are 3 D



(b) 3-D considerations

42

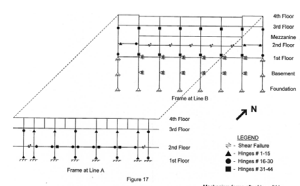
Chapter 5: the hub of the methodology

Mechanism Analysis

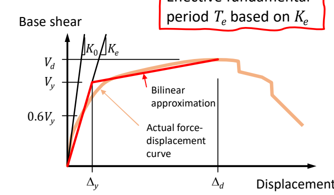
Next

43

Effective fundamental period (5.6)



(a) Nonlinear static analysis (Degenkolb)



Effective fundamental period T_e based on K_e

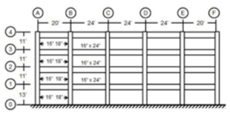
(b) Nonlinear static analysis pushover curve and effective stiffness K_e

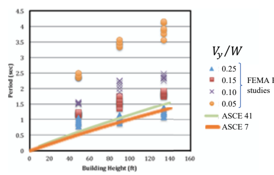
Methods: 1) FEMA 2018 period equations (typical method)
2) Nonlinear static analysis (if results available)
Don't use ASCE 7 or linear elastic computer model to get T_e.

44

Effective fundamental period - frames (5.6)

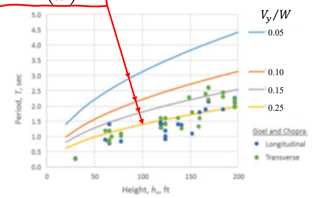
(a) FEMA 2018 period study





(b) Comparison with field data

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



45

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.

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

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

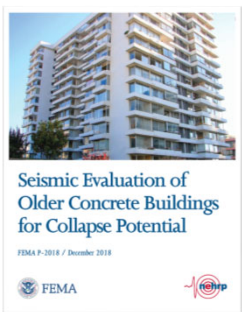
where:

- 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

46

Effective fundamental period – other systems (5.6.1)

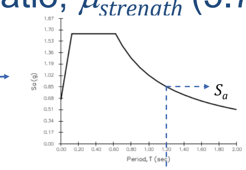
See FEMA 2018 for T_e for pier-spandrel systems and infilled frame systems.

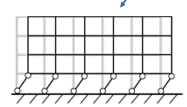


47

Period leads to Spectral demand which leads to: Global demand-capacity ratio, $\mu_{strenath}$ (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.

48

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 ($V_p/V_n \le 0.6$)	> 5.5
	Some discontinuous wall-on-column conditions	Any
	Some discontinuous wall-on-girder conditions	Any

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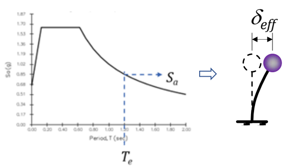
$\mu_{strength}$ is an important parameter in FEMA P-2018 because:

(Check all that are true)

- ❑ Lateral strength has a large influence on collapse probability
- ❑ It is a measure of global demand/capacity ratio
- ❑ Anything with a Greek letter must be important
- ❑ Global strength affects the collapse probability caused by most structural deficiencies
- ❑ 0.1/(base shear) is roughly equal to probability of collapse

Story drift calculation (Chapters 6, 7, …)

Period also leads to: Global seismic drift demand (6.4, 7.4, …)

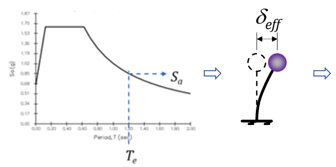


$$\delta_{eff} = C_1 C_2 S_a \frac{T_e^2}{4\pi^2} g$$

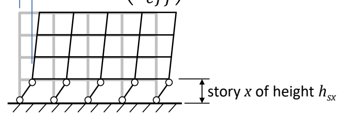
- δ_{eff}: Equivalent SDOF displacement
- $S_a \frac{T_e^2}{4\pi^2} g$: SDOF spectral displacement
- C_1: Coefficient to amplify short-period drift (from ASCE 41) $C_1 = 1 + \frac{\mu_{strength} - 1}{aT_e^2}$
- C_2: Coefficient to amplify drift due to degradation (from ASCE 41) $C_2 = 1 + \frac{1}{800}\left(\frac{\mu_{strength}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

(All from ASCE 41)

Story drift demand (6.5, 7.5, …)



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



Story drift demand (6.5, 7.5, …)

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

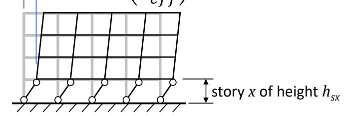


Table 6-1 Values of Coefficient α for Frame Systems

No. of Stories in the Building	Yield Mechanism[2]	Values of α[1]	
		Critical Stories	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	$\boxed{2.0}$	$1-0.5\frac{x-2}{n-2}$
	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 example, the controlling mechanism is Mechanism 1, $\alpha_x = 2.0$, $h_{sx} = 18'$, $h_{eff} = 0.7 \times 54' = 38'$.
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 $\frac{\delta_x}{h_{sx}} = 0.03$.

Drift 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

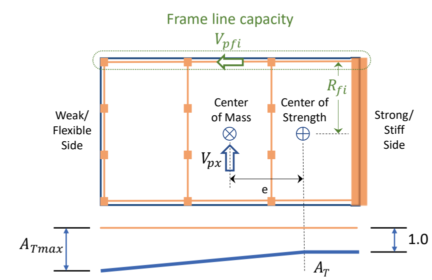
Drift Adjustment for Torsion

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 $A_{Tmax} = 2.75 \times TR + 0.5 \geq 1.0$

We now have the drift demands on individual gravity carrying components.

Abbie Liel will now discuss the Capacity Side

FEMA

nehrp

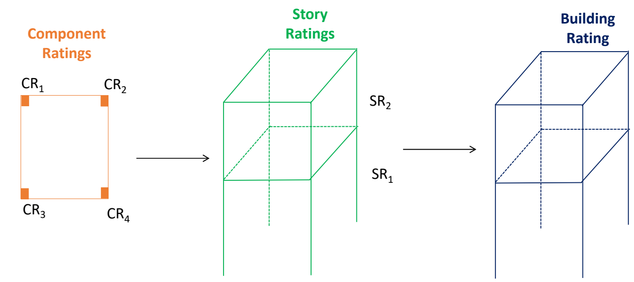
57

FEMA P-2018: Drift Capacities and Rating Systems

Abbie Liel, University of Colorado, Boulder

1

Overview



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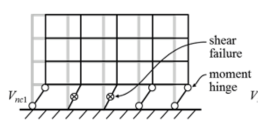
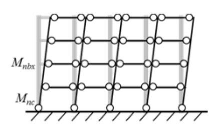
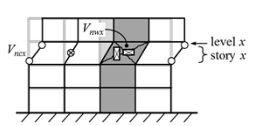
6.2 Identification of Critical Stories



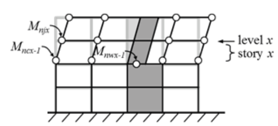
Mechanism 1: 1st story



Mechanism 2: 1st story



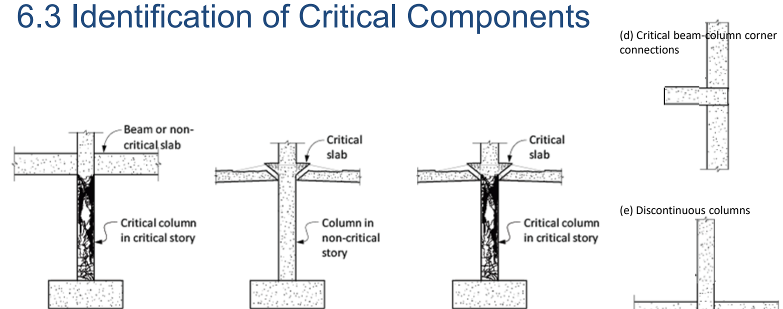
Mechanism 3: story where mechanism forms



Mechanism 4: lowest story in which yielding occurs

3

6.3 Identification of Critical Components



(a) Critical column
(b) Critical slab-column connection
(c) critical column and critical slab-column at same column
(f) Critical wall and wall segments

4

6.8 Component Ratings

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

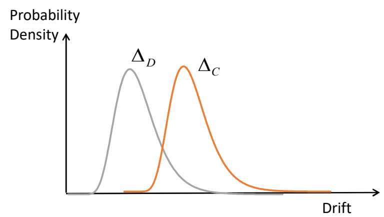


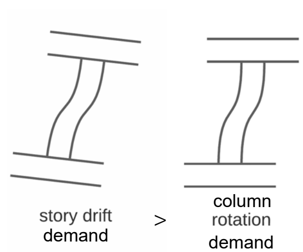
Illustration of structural reliability methods to assess probability that drift demand exceeds drift capacity

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



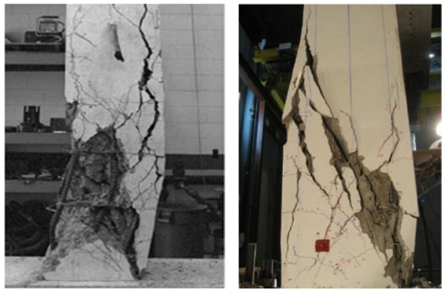
6.6.1 Rotation Demands on Critical Columns

Table 6-2 Drift Factor for Columns

Ratio of Column Strengths to Beam Strengths[2] $\Sigma M_c/\Sigma M_b$	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

9

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

10

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	

11

6.8 Column Ratings

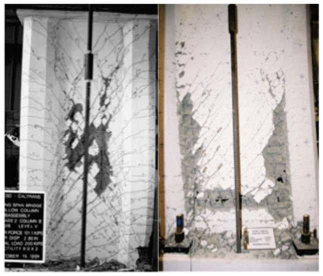
Table 6-6 Column Ratings

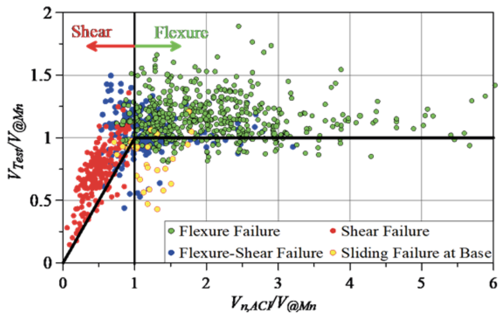
Drift Demand to Drift Capacity Ratio Δ_D/Δ_C	Column Rating *CR*
$\Delta_D/\Delta_C \le 0.25$	0.0
$0.4 \ge \Delta_D/\Delta_C > 0.25$	0.1
$0.5 \ge \Delta_D/\Delta_C > 0.4$	0.2
$0.7 \ge \Delta_D/\Delta_C > 0.5$	0.3
$0.9 \ge \Delta_D/\Delta_C > 0.7$	0.4
$1.1 \ge \Delta_D/\Delta_C > 0.9$	0.5
$1.4 \ge \Delta_D/\Delta_C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

12

7.7.4 Wall Drift Capacities

- Empirical relationships developed based on UCLA RC walls database

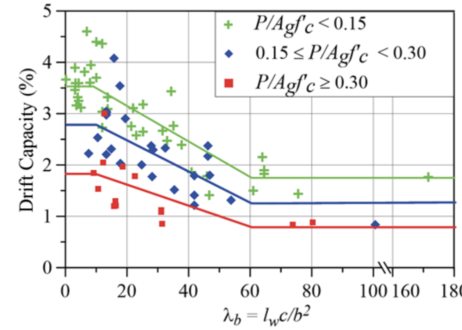




Example wall tests, and scatter plot of data

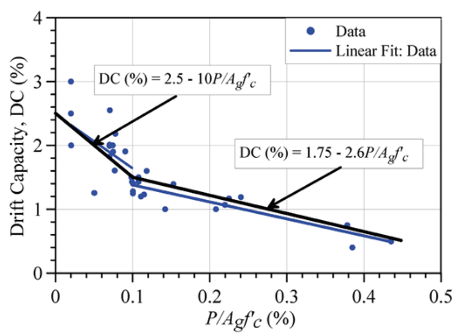
7.7.4 Wall Drift Capacities

- Flexure controlled walls, trends with key parameters



7.7.4 Wall Drift Capacities

- Shear controlled walls, trends with key parameters



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*
$\Delta_D/\Delta_C \le 0.25$	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

Poll

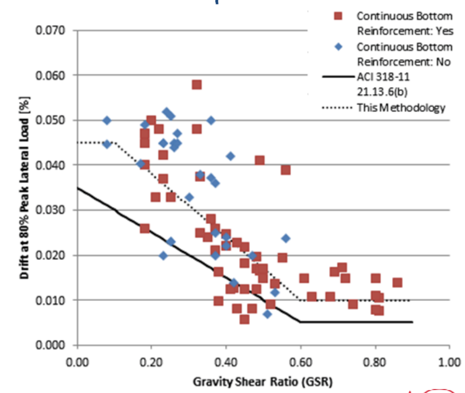
True or false: A higher column or wall rating indicates worse performance.

- ❑ True
- ❑ False

17

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



18

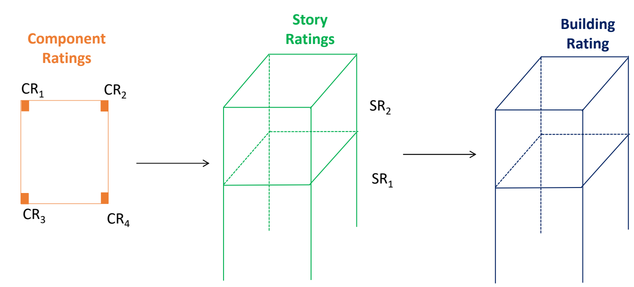
6.7.2 Slab-Column Connection Drift Capacities

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	$0.01h_{sx}$

19

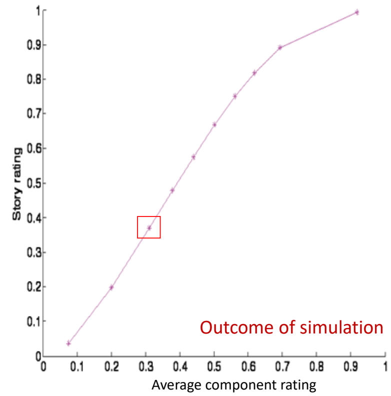
6.9 Story Ratings



20

6.9 Story Ratings

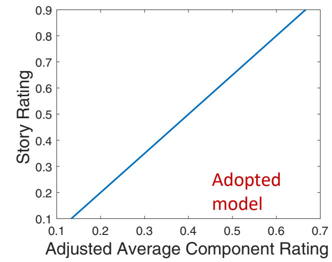
- What combination of component ratings produces story failure?
  - Derivation involved probabilistic (Monte Carlo) simulation to determine story ratings, based on column (wall) ratings
  - Story failure occurs if components carrying 25% of gravity load in a story fail



21

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:

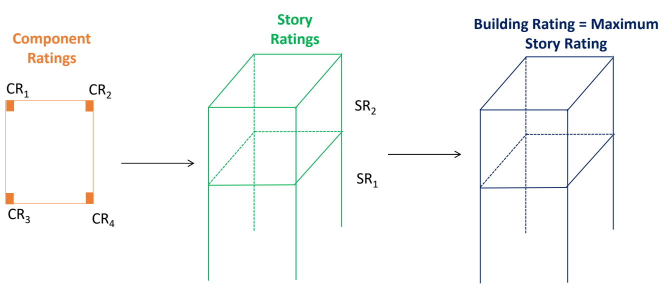
$$R_{adj} = R_{avg} + 0.625R_{avg}(\mathrm{COV} - 0.4)$$

where:

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

22

10 Building Ratings



23

FEMA P-2018: Example Application for a Frame Building

Presented by: Abbie Liel

Example by: Rami Elhassan and Yangbo Chen, IDS Group

24

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 rating

Chp. 6

25

Building Description

- 5-Story 1960s 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

26

Building Description

- 5-Story 1960s 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

27

Building Description

Typical Floor

28

Evaluation Procedures for Frame Systems

5. Frame system definition, strength and period calculations

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6.9 Determine story ratings

Chp. 6

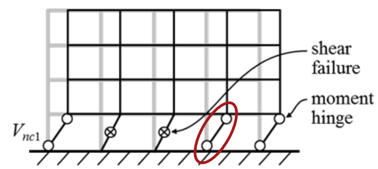
10. Determine building rating

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

29

Strength and Period Calculations (Chp. 5)

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 Shear if *flexural controls*:

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

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

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

There are total of 9 Frames:

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

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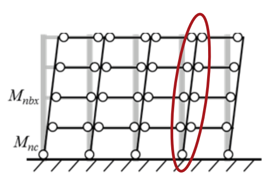
30

Strength and Period Calculations (Chp. 5)

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 $h_{eff} = 0.7h_n$

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} = 157 kips - Total for Frame on Gridline 2

There are total of 9 Frames:

V_{P1} = 1,420 kips < 2,470 kips from Mechanism 1

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31

Strength and Period Calculations (Chp. 5)

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

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

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32

Strength and Period Calculations (Chp. 5)

- Calculate the Effective Fundamental Period for the frame building:

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

33

Strength and Period Calculations (Chp. 5)

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

34

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
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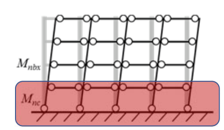
6.9 Determine story ratings
10. Determine building rating

Chp. 6

35

Identification of Critical Story & Critical Components

Story and Components for which Ratings are Required (Section 6.2 & 6.3):

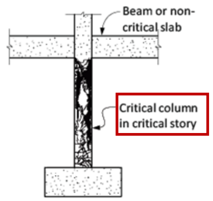


Critical story:
first above base
(Section 6.2)

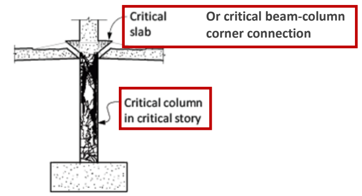
36

Identification of Critical Story & Critical Components

Story and Components for which Ratings are Required (Section 6.2 & 6.3):



Critical column



critical column and critical slab-column at same column

37

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
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6.8 Determine column ratings
6.9 Determine story ratings
10. Determine building rating

Chp. 6

38

Global Seismic Drift Demand

Calculate Global Seismic Drift Demand (Section 6.4)

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

Equivalent SDOF displacement

SDOF spectral displacement

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

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

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)

$C_1 = 1.0 \ (T_e > 1.0)$

$C_2 = 1.0 \ (T_e > 0.7)$

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

$= \mathbf{\mathit{16.9}}\ in$

39

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
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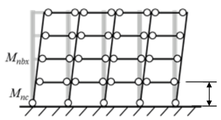
10. Determine building rating

Chp. 6

40

Drift Demand on Critical Story

Critical Story Drift Demand Adjustment – α (Section 6.5)



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

$\alpha_x = 1.5$, $h_{sx} = 17.25'$, $h_{eff} = 0.7 \times 70.25' = 49.2'$

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.

Drift Demand on Critical Story

b. Critical Story Drift Demand Adjustment – P-Δ (Section 6.5)

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

Amplified story drift

Gravity load above level 1

1st story height

Plastic mechanism shear strength at 1st story

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

W_1 = 14,610 kips

δ_1 = 8.9 in (already amplified by α)

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 $\frac{\delta_1}{h_{s1}} = 0.08$

Evaluation Procedures for Frame Systems

5. Frame system definition, strength and period calculations
6.2 Identify critical stories
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10. Determine building rating

$\Bigg\}$ Chp. 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 <u>Many Component</u>: $\gamma = 1.0$

For <u>Critical Columns</u>: $\frac{\sum M_c}{\sum M_b} = 3.72$ Thus, $\gamma = 0.30$ 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

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Chp. 6

Drift Capacity of Critical Components

a. Drift Capacity of Critical Columns (Section 6.7.1)

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

Shear Ratio: $V_p/V_n = 0.22 < 0.6$

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

Transverse Reinf. Ratio:
$\rho_t = A_v/(b_w s) = 0.0025 > 0.002$

Transverse Reinf. Spacing: $s/d < 0.5$

$>> \theta_c = \mathbf{0.061}$

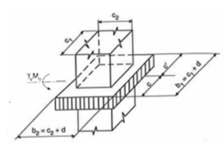
$\Delta_c = 193\ (0.061 + 0.01) = \mathbf{12.6}$ *in*

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	

Drift Capacity of Critical Components

b. Drift Capacity of Critical Slab-Column Connections (Section 6.7.2)

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



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

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

$v_g / v_c = 0.129$

At first story, $h_{sx} = 194$ *in* >>> $\Delta_c = 0.043\ h_{s1} = \mathbf{8.3}$ *in*

Drift Capacity of Critical Components

c. Drift Capacity of Critical Beam-Column Corner Connections (Section 6.7.3)

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

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
$\Delta_c = \mathbf{\textit{12.0}}$ in

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Chp. 6

49

Determine Column Ratings (Section 6.8)

Every critical component 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

Typical Column $\frac{\Delta D}{\Delta C}$ = 1.8-1.9

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

50

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Chp. 6

51

Story Rating (Section 6.9)

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

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

R_{avg} = 0.805

Average component rating, weighted by gravity load carried

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

$R_{adj} =$ 0.8

Adjustment to average based on coefficient of variation

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

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

Story rating

SR = 0.9

52

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Chp. 6

Determine Building Rating (Chapter 10)

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

FEMA P-2018:
Wrap-up

Bill Holmes, Structural Engineer, Rutherford + Chekene

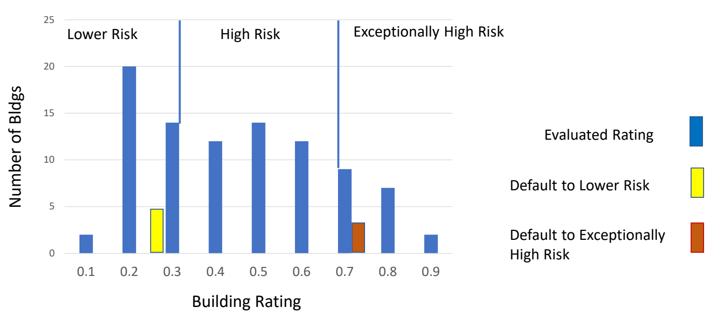
FEMA

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.

2



Example Inventory

3

The owner (or jurisdiction) could then…

- Further evaluate or mitigate the risk from the inventory by starting at the highest ratings (most risk) and over time work through the lower rated buildings.
- Other factors, such as occupancy and building populations, could also be integrated into priorities.

4

Uses of FEMA P-2018 Methodology

- Primary intended use is to rate individual older concrete buildings with respect to the risk of story collapse.
  - Jurisdictions wanting to set priorities for mitigation of life safety risk.
  - Owners of inventories of buildings wanting to understand relative risk of each building
- Provides a method for engineers to differentiate between buildings that may fail consensus standard criteria.
  - "How bad is bad?"
- Unintended consequence
  - Suggests a format that consensus "pass/fail" standards could use to incorporate probabilistic variations in projecting performance.

Thank you for your attention

Closing & Thank you

- **Handouts**
  - Available in the Handouts pod & distributed via email today
- **PDH certificates**
  - Provided for participants of live webinar (not the recording)
  - Watched in a group? Request additional certificates by end of day today (7/1) using link provided in Chat pod
  - Distributed via email within one month
- **Q&A**
  - Distributed via email within one month