Existing Buildings 02
Linear Analyses Procedures

Date: 27 Feb 2022
Session 39

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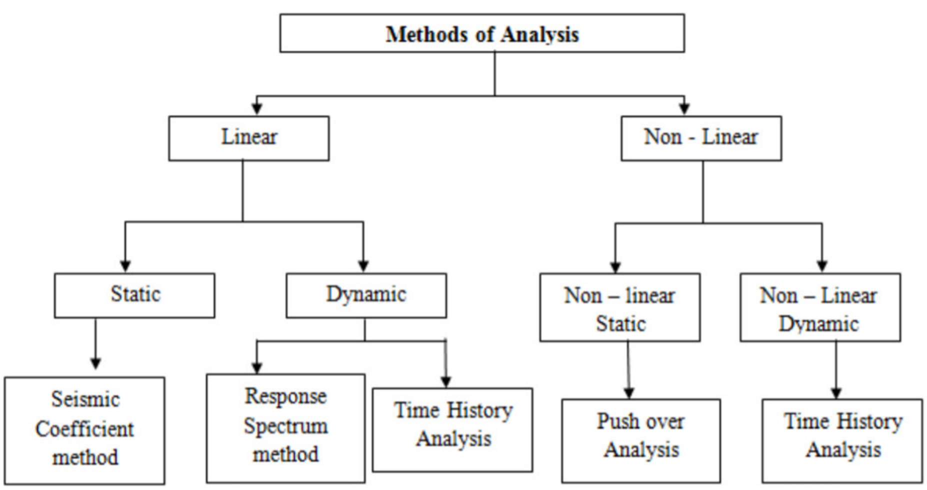

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The Applicability of the Linear Procedures

If the building does not have any of these:

1. In-Plane Discontinuity Irregularity
2. Out-of-Plane Discontinuity Irregularity
3. Weak Story Irregularity*
4. Torsional Strength Irregularity**

If either * or ** exists and
If a component DCR exceeds the lesser of 3.0 and the m-factor
for the component action then linear
procedures are not applicable and shall not be used.

$$\text{DCR} = \frac{Q_{UD}}{Q_{CE}}$$

Q_{UD} = Force caused by gravity loads and earthquake forces
Q_{CE} = Expected strength of the component or element

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The Applicability of the Linear Static Procedure

If the building does not have any of these:

1. The fundamental period of the building, T, is greater than or equal to 3.5 times Ts.
2. The ratio of the horizontal dimension at any story to an adjacent story exceeds 1.4.
3. The building has a torsional stiffness irregularity in any story.
4. The building has a vertical stiffness irregularity.
5. The building has a nonorthogonal seismic-force-resisting system.

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Course Title: Existing Buildings Track 2 Linear Analyses Procedures

▪ **Course Topics:**

1. The steps in Linear Analyses Procedures.
2. The limitations of each linear analysis method.
3. What are the issues for linear procedures in estimating the deformation-controlled parameters?
4. What are the issues for linear procedures in estimating the force-controlled parameters?
5. Base shear estimation formula and its coefficients.
6. The acceptance criteria for linear analysis.

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Performance Objective

Probability of Exceedance	Mean Return Period (years)
50%/30 years	43
50%/50 years	72
20%/50 years	225
10%/50 years	475
5%/50 years	975
2%/50 years	2,475

Earthquake Hazard Level	Target Building Performance Levels: Operational Level (1-A)	Immediate Occupancy Performance Level (1-B)	Life Safety Performance Level (3-C)	Collapse Prevention Performance Level (5-E)
50%/50 year	a	b		d
20%/50 year	e	f		h
BSE-1 (~10%/50 year)				l
BSE-2 (~2%/50 year)	m	n	o	p

Life Safety Level (3-C)
Moderate
Some residual strength and stiffness left in all stories. Gravity-load-bearing elements function. No out-of-plane failure of walls. Some permanent drift. Damage to partitions. Continued occupancy might not be likely before repair. Building might not be economical to repair.
Falling hazards, such as parapets, mitigated, but many architectural, mechanical, and electrical systems are damaged.
Somewhat more damage and slightly higher life-safety risk.

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Design Base Shear verses **Assessment** Base Shear

BNBC 2020

$$V = S_a W$$

$$S_a = \frac{2}{3}\frac{ZI}{R}C_s$$

ASCE 41-17

$$V = C_1 C_2 C_m S_a W$$

S_a = Design spectral acceleration (in units of g)

β = Coefficient used to calculate lower bound for S_a

Z = Seismic zone coefficient

I = Structure importance factor

R = Response reduction factor which depends on structural system

C_s = Normalized acceleration response spectrum

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Design Base Shear verses **Assessment** Base Shear

BNBC 2020

$$V = S_a W$$

$$S_a = \frac{2}{3}\frac{ZI}{R}C_s$$

ASCE 41-17

$$V = C_1 C_2 C_m S_a W$$

$$m\kappa Q_{CE} > Q_{UD}$$

m = Component capacity modification factor to account for expected ductility associated with this action at the selected Structural Performance Level.

R = Response reduction factor which depends on structural system

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Pseudo Seismic Force

$$V = C_1 C_2 C_m \boxed{S_a} W$$

$$V = C_1 C_2 C_3 C_m S_a W$$

Probability of Exceedance	Mean Return Period (years)
50%/30 years	43
50%/50 years	72
20%/50 years	225
10%/50 years	475
5%/50 years	975
2%/50 years	2,475

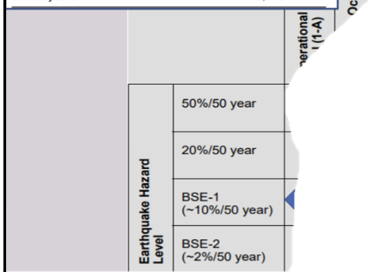

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Table 6.2.16: Site Dependent Soil Factor and Other Parameters Defining Elastic Response Spectrum

Soil type	S	T_B(s)	T_C(s)	T_D(s)
SA	1.0	0.15	0.40	2.0
SB	1.2	0.15	0.50	2.0
SC	1.15	0.20	0.60	2.0
SD	1.35	0.20	0.80	2.0
SE	1.4	0.15	0.50	2.0

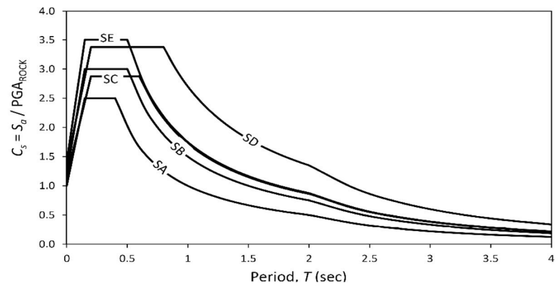

Figure 6.2.26 Normalized design acceleration response spectrum for different site classes.

$\boxed{S_a}$ = Response spectrum acceleration, at the fundamental period and damping ratio of the building in the direction under consideration.

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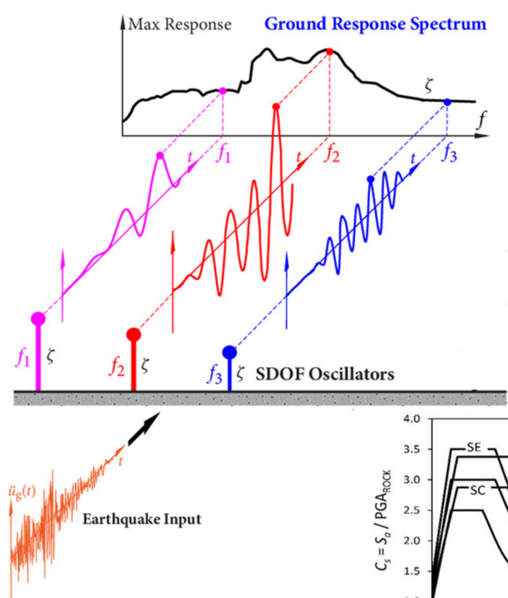

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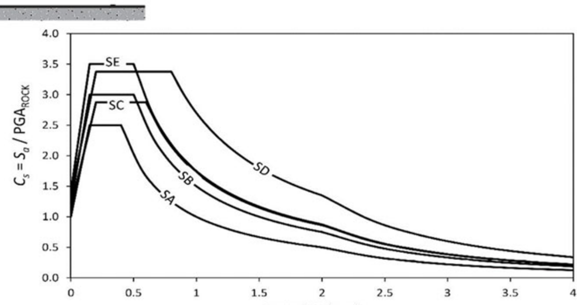
Pseudo Seismic Force

$$V = C_1 C_2 C_m \boxed{S_a} W$$

S_a = Response spectrum acceleration



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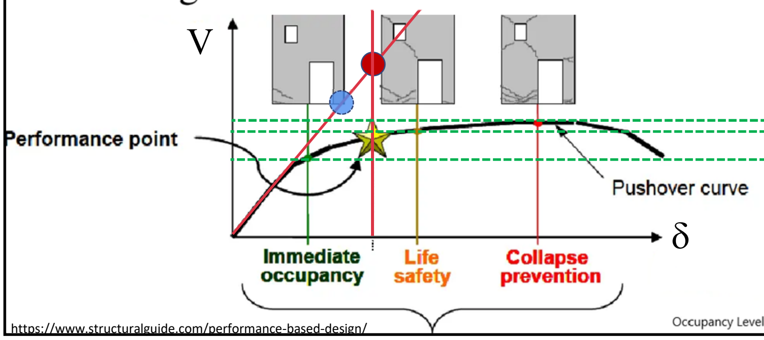
Pseudo Seismic Force

$$V = \boxed{C_1 C_2} C_m S_a W$$

C_1 = Modification factor to relate expected maximum inelastic displacements to displacements calculated for linear elastic response.

C_2 = Modification factor to represent the effect of pinched hysteresis shape, cyclic stiffness degradation, and strength deterioration on maximum displacement.



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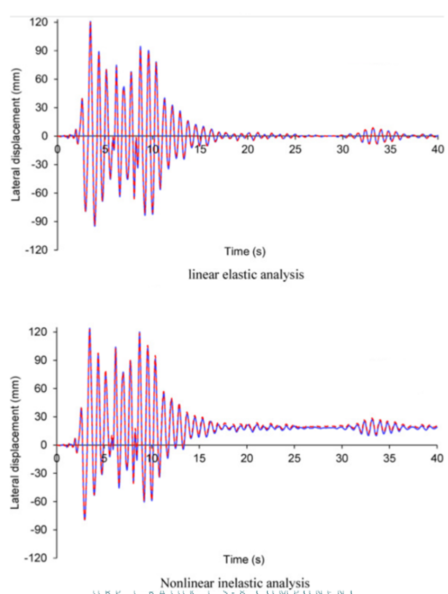
$\boxed{C_1}$ = Modification factor to relate expected maximum inelastic displacements to displacements calculated for linear elastic response.



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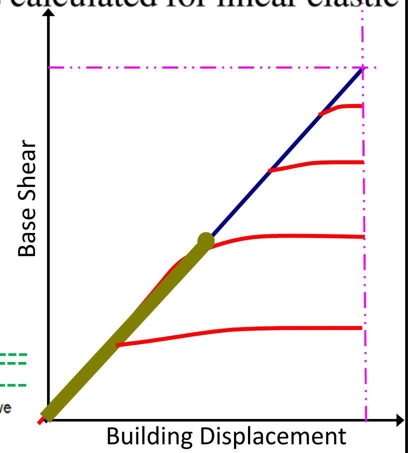
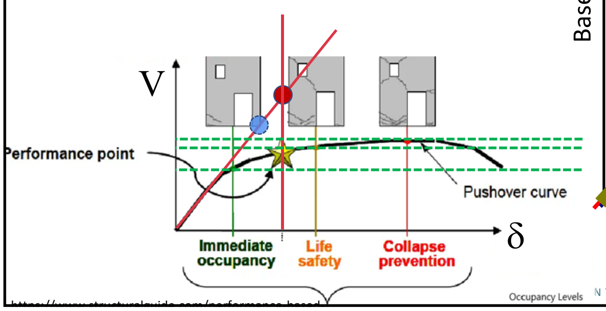
Pseudo Seismic Force

$$\boxed{V = \boxed{C_1} C_2 C_m S_a W}$$

C_1 = Modification factor to relate expected maximum inelastic displacements to displacements calculated for linear elastic response.





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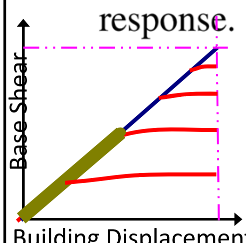
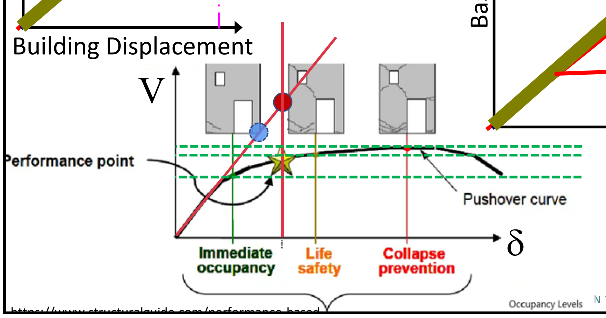
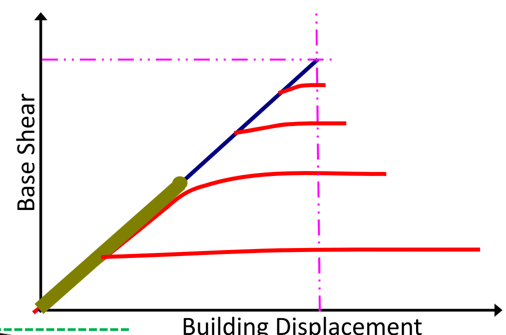
Pseudo Seismic Force

$$\boxed{V = \boxed{C_1} C_2 C_m S_a W} \qquad C_1 = 1 + \frac{\mu_{strength} - 1}{aT^2}$$

C_1 = Modification factor to relate expected maximum inelastic displacements to displacements calculated for linear elastic response.







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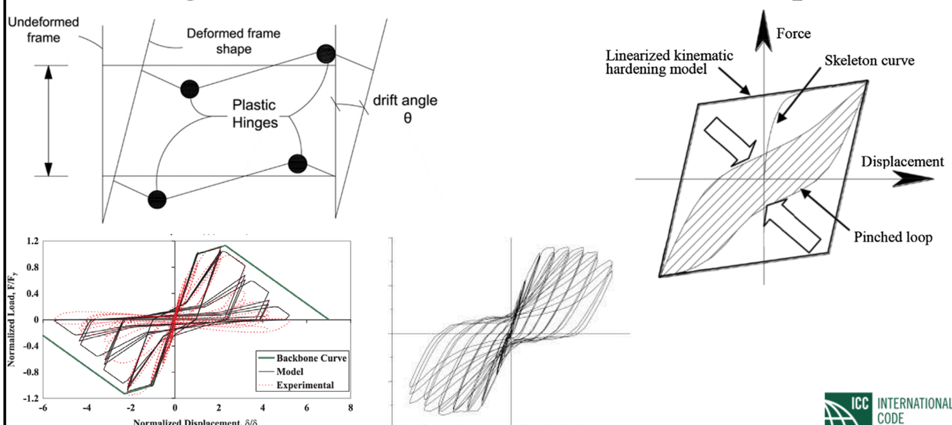
Pseudo Seismic Force

$$V = C_1 \boxed{C_2} C_m S_a W$$

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

C_2 = Modification factor to represent the effect of pinched hysteresis shape, cyclic stiffness degradation, and strength deterioration on maximum displacement.



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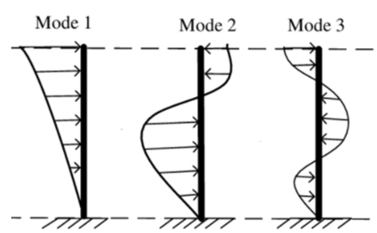
Pseudo Seismic Force

$$V = C_1 C_2 \boxed{C_m} S_a W$$



C_m = Effective mass factor to account for higher modal mass participation effects obtained from Table 7-4.
C_m shall be taken as 1.0 if the fundamental period, T, is greater than 1.0 s;

Table 7-4. Values for Effective Mass Factor C_m

No. of Stories	Concrete Moment Frame	Concrete Shear Wall	Concrete Pier-Spandrel	Steel Moment Frame	Steel Concentrically Braced Frame	Steel Eccentrically Braced Frame	Other
1–2	1.0	1.0	1.0	1.0	1.0	1.0	1.0
3 or more	0.9	0.8	0.8	0.9	0.9	0.9	1.0

Note: C_m shall be taken as 1.0 if the fundamental period, T, in the direction of response under consideration is greater than 1.0 s.

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Pseudo Seismic Force

$$\boxed{V = C_1 C_2 C_m S_a W}$$

Vertical Distribution of Seismic Forces

$$F_x = C_{vx} V \qquad (7\text{-}24)$$

$$C_{vx} = \frac{w_x h_x^k}{\sum_{i=1}^{n} w_i h_i^k} \qquad (7\text{-}25)$$

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The load combinations in Linear Static Procedure

Gravity Loads

$$Q_G = 1.1(Q_D + Q_L + Q_S) \qquad (7\text{-}1)$$

$$Q_G = 0.9 Q_D \qquad (7\text{-}2)$$

$$Q_G = Q_D + Q_L + Q_S \qquad (7\text{-}3)$$

Q_D = Action caused by dead loads;
Q_L = Action caused by live load, equal to 25% of the unreduced live load obtained in accordance with ASCE 7 but not less than the actual live load; and
Q_S = Action caused by effective snow load.

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Actions (responses) caused by loads

$$V = C_1 C_2 C_m S_a W$$

$$Q_G = 1.1(Q_D + Q_L + Q_S)$$

$$Q_G = 0.9 Q_D$$

$$Q_G = Q_D + Q_L + Q_S$$

Q_E Q_G

Q_G = Action caused by gravity loads

Q_E = Action caused by the response to the selected Seismic Hazard Level

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Acceptance Criteria for **Deformation-Controlled** actions estimation of their Demand and checking with their Capacity

$$Q_{UD} = Q_G + Q_E$$

Q_G = Action caused by gravity loads

Q_E = Action caused by the response to the selected Seismic Hazard Level

$$m\kappa Q_{CE} > Q_{UD}$$

m = Component capacity modification factor to account for expected ductility associated with this action at the selected Structural Performance Level.

Q_{CE} = Expected strength of component deformation-controlled action

κ = Knowledge factor

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Table 10-13. Numerical Acceptance Criteria for Linear Procedures—Reinforced Concrete Beams

Conditions			m-Factors[a]				
			Performance Level				
				Component Type			
				Primary		Secondary	
			IO	LS	CP	LS	CP
Condition i. Beams controlled by flexure[b]							
$\frac{\rho - \rho'}{\rho_{bal}}$	Transverse reinforcement[c]	$\frac{V^d}{b_w d \sqrt{f'_{cE}}}$					
≤0.0	C	≤3 (0.25)	3	6	7	6	10
≤0.0	C	≥6 (0.5)	2	3	4	3	5
≥0.5	C	≤3 (0.25)	2	3	4	3	5
≥0.5	C	≥6 (0.5)	2	2	3	2	4
≤0.0	NC	≤3 (0.25)	2	3	4	3	5
≤0.0	NC	≥6 (0.5)	1.25	2	3	2	4
≥0.5	NC	≤3 (0.25)	2	3	3	3	4
≥0.5	NC	≥6 (0.5)	1.25	2	2	2	3
Condition ii. Beams controlled by shear[b]							
Stirrup spacing ≤ $d/2$			1.25	1.5	1.75	3	4
Stirrup spacing > $d/2$			1.25	1.5	1.75	2	3
Condition iii. Beams controlled by inadequate development or splicing along the span[b]							
Stirrup spacing ≤ $d/2$			1.25	1.5	1.75	3	4
Stirrup spacing > $d/2$			1.25	1.5	1.75	2	3
Condition iv. Beams controlled by inadequate embedment into beam–column joint[b]							
			2	2	3	3	4

m = Component capacity modification factor to account for expected ductility associated with this action at the selected Structural Performance Level.

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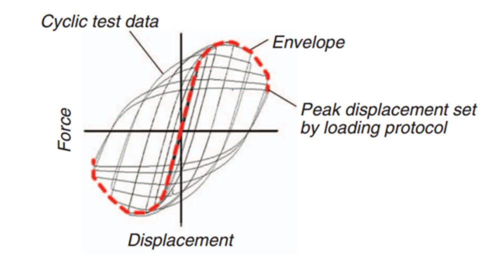
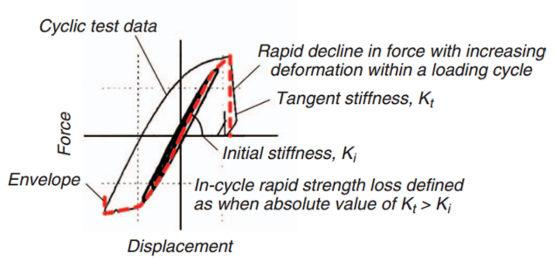
m = Component capacity modification factor to account for expected ductility associated with this action at the selected Structural Performance Level.



(a) Ductile behavior



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(b) Rapid Strength Loss Behavior

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Acceptance Criteria for **Deformation-Controlled** actions estimation of their Demand and checking with their Capacity

$$Q_{UD} = Q_G + Q_E \longrightarrow m\boxed{\kappa}Q_{CE} > Q_{UD}$$

$$\kappa = \text{Knowledge factor}$$

Table 6-1. Data Collection Requirements

Data	Level of Knowledge: Minimum		Level of Knowledge: Usual		Level of Knowledge: Comprehensive	
Performance Level	Life Safety (S-3) or lower		Damage Control (S-2) or lower		Immediate Occupancy (S-1) or lower	
Analysis Procedures	LSP, LDP		All		All	
Testing	No tests[a]		Usual testing		Comprehensive testing	
Drawings	Design drawings	Field survey drawings prepared in absence of design drawings	Design drawings	Field survey drawings prepared in absence of design drawings	Design drawings	Field survey drawings prepared in absence of design drawings
Condition Assessment[b]	Visual	Comprehensive	Visual	Comprehensive	Visual	Comprehensive
Material Properties	From design drawings (or documents)[c]	From default values	From design drawings (or documents) and tests	From usual tests	From design drawings (or documents) and tests	From comprehensive tests
Knowledge Factor (κ)[d]	0.9[e,f]	0.75	1.00	1.00	1.00	1.00

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Acceptance Criteria for **Deformation-Controlled** actions estimation of their Demand and checking with their Capacity

$$Q_{UD} = Q_G + Q_E \longrightarrow m\boxed{\kappa}Q_{CE} > Q_{UD}$$

$$\kappa = \text{Knowledge factor}$$

Table 7-7. Calculation of Component Action Capacity: Nonlinear Procedures

Parameter	Deformation Controlled	Force Controlled
Deformation capacity (existing component)	$\kappa \times$ Deformation limit	N/A
Deformation capacity (new component)	Deformation limit	N/A
Strength capacity (existing component)	N/A	$\kappa \times Q_{CL}$
Strength capacity (new component)	N/A	Q_{CL}

Table 7-6. Calculation of Component Action Capacity: Linear Procedures

Parameter	Deformation Controlled	Force Controlled
Existing material strength	Expected mean value with allowance for strain hardening	Lower bound value (approximately mean value minus 1σ level)
Existing action capacity	κQ_{CE}	κQ_{CL}
New material strength	Expected material strength	Specified material strength
New action capacity	Q_{CE}	Q_{CL}

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Acceptance Criteria for **Force-Controlled** actions
estimation of their Demand and checking with their Capacity

1. Q_{UF} shall be taken as the maximum action that can be developed in a component based on a limit-state analysis considering the expected strength of the components delivering force to the component under consideration, or the maximum action developed in the component as limited by the nonlinear response of the building.
2. Alternatively,

$$Q_{UF} = Q_G \pm \frac{\chi Q_E}{C_1 C_2 J}$$

χ = Factor for adjusting action caused by response for the selected Structural Performance Level;
= 1.0 where J is taken as smallest DCR; otherwise,
= 1.0 for Collapse Prevention;
= 1.3 for Life Safety or Immediate Occupancy;

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Acceptance Criteria for **Force-Controlled** actions
estimation of their Demand and checking with their Capacity

$$Q_{UF} = Q_G \pm \frac{\chi Q_E}{C_1 C_2 J}$$

J = Force-delivery reduction factor, greater than or equal to 1.0, taken as the smallest demand–capacity ratio (DCR) of the components in the load path delivering force to the component in question.

Alternatively, values of J equal to 2.0 for a high level of seismicity, 1.5 for a moderate level of seismicity, and 1.0 for a low level of seismicity shall be permitted where not based on calculated DCRs. J shall be taken as 1.0 for the Immediate Occupancy Structural Performance Level in these instances.

In any case where the forces contributing to Q_{UF} are delivered by components of the seismic-force-resisting system that remain elastic, J shall be taken as 1.0.

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Acceptance Criteria for **Force-Controlled** actions
estimation of their Demand and checking with their Capacity

$$Q_{UF} = Q_G \pm \frac{\chi Q_E}{C_1 C_2 J}$$

7.5.2.2.2 Acceptance Criteria for Force-Controlled Actions for LSP or LDP. Force-controlled actions in primary and secondary components shall satisfy Eq. (7-37):

$$\kappa Q_{CL} > Q_{UF} \qquad (7\text{-}37)$$

where

Q_{CL} = Lower-bound strength of a force-controlled action of an element at the deformation level under consideration.

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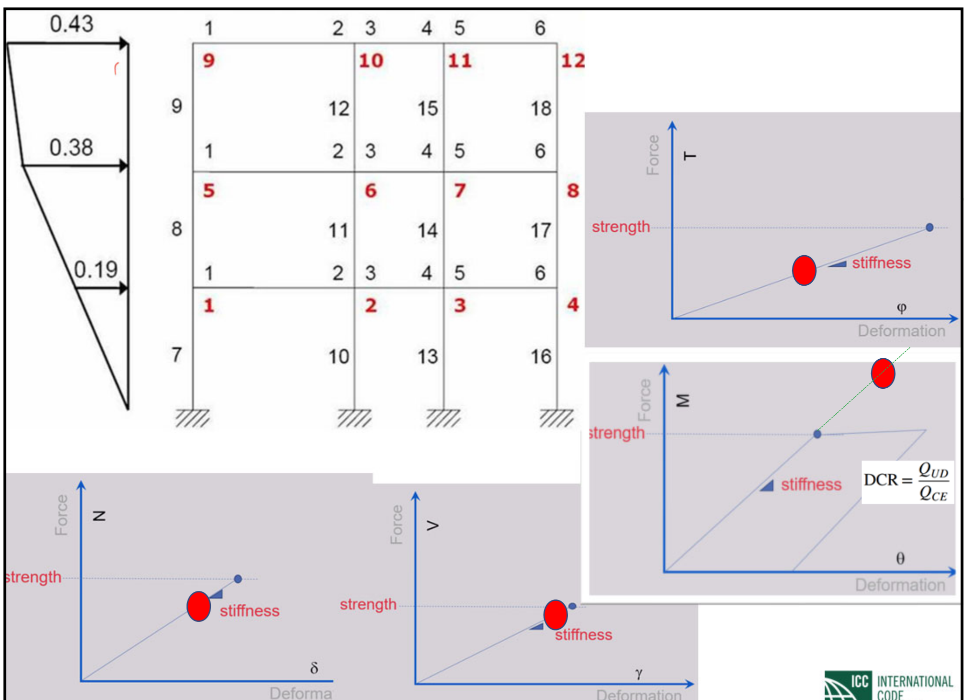

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Summary 1/5

• The two main parts of each "Performance Objective".

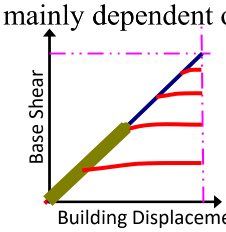
		Target Building Performance Levels			
		Operational Performance Level (1-A)	Immediate Occupancy Performance Level (1-B)	Life Safety Performance Level (3-C)	Collapse Prevention Performance Level (5-E)
Earthquake Hazard Level	50%/50 year	a	b		d
	20%/50 year	e	f		h
	BSE-1 (~10%/50 year)				l
	BSE-2 (~2%/50 year)	m	n	o	p

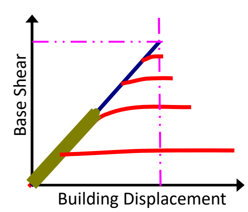
• The difference between R-factor in "BNBC 2020 base shear formula" and m-factor in "systematic evaluation" by linear analysis.

Conditions			IO	LS	CP
Condition i. Beams controlled by flexure[b]					
$\frac{\rho - \rho'}{\rho_{bal}}$	Transverse reinforcement[c]	$\frac{V^d}{b_w d \sqrt{f'_{cE}}}$			
≤0.0	C	≤3 (0.25)	3	6	7

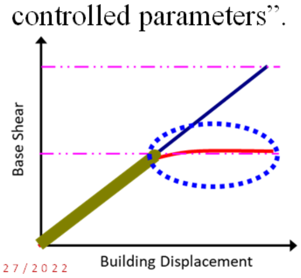
Summary 2/5

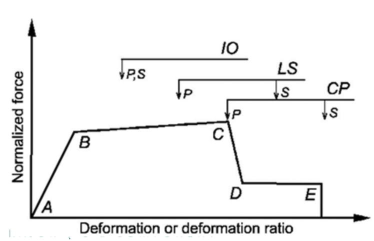
• In the base shear formula for systematic linear analysis, the factor "C1" is "the Modification factor to relate maximum inelastic displacements to displacements calculated for linear elastic response". The factor "C1" is mainly dependent on?





• The linear analysis method is not capable of determining the "deformation-controlled parameters".





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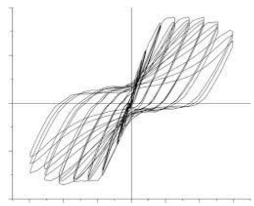
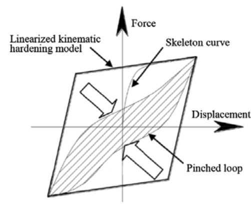
Summary 3/5

- In the base shear formula for systematic linear analysis, the factor “C2” is “the modification factor to represent the effect of pinched hysteresis shape, and strength deterioration on maximum displacement”. The factor “C2” is mainly dependent on?





- If a “Force-Controlled Action” does not satisfy the acceptance criteria.

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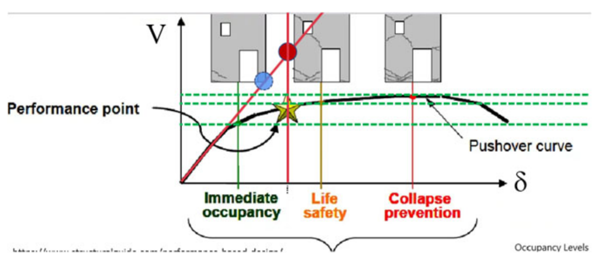
Summary 4/5

- Why the base shear increased by the factors “C1” and “C2”?



- In the base shear formula for linear analysis, the “Earthquake Hazard Level” is represented by?

$$\boxed{V = C_1 C_2 C_m S_a W}$$

S_a = Response spectrum acceleration

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Summary 5/5

- The linear analysis method "is not" capable of determining the "force-controlled parameters".

$$Q_{UD} = Q_G + Q_E \qquad Q_{UF} = Q_G \pm \frac{\chi Q_E}{C_1 C_2 J}$$

- For a linear analysis, when "dynamic methods" should be used instead of "static methods"?

Mass and stiffness irregularity

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Course Title: Existing Buildings Track 2 Linear Analyses Procedures

- **Course Outcomes:**

1. Understand what the shortcomings of the linear analysis methods are.
2. Can calculate the base shear of buildings for earthquakes with different return periods.
3. Differentiate between the way force-controlled parameters are treated compared to deformation-controlled response parameters.
4. Determine the load combinations needed for estimation of force-controlled and deformation-controlled response parameters.
5. Apply the linear procedures for assessment of existing buildings.

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Questions?
Thank you

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