Existing Buildings 03
Nonlinear Analyses Procedures

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Session 41

A.S. Moghadam
International Institute of Earthquake Engineering and Seismology (IIEES)
and
S-04 Team Leader, JV of NKY-Protek-Sheltech

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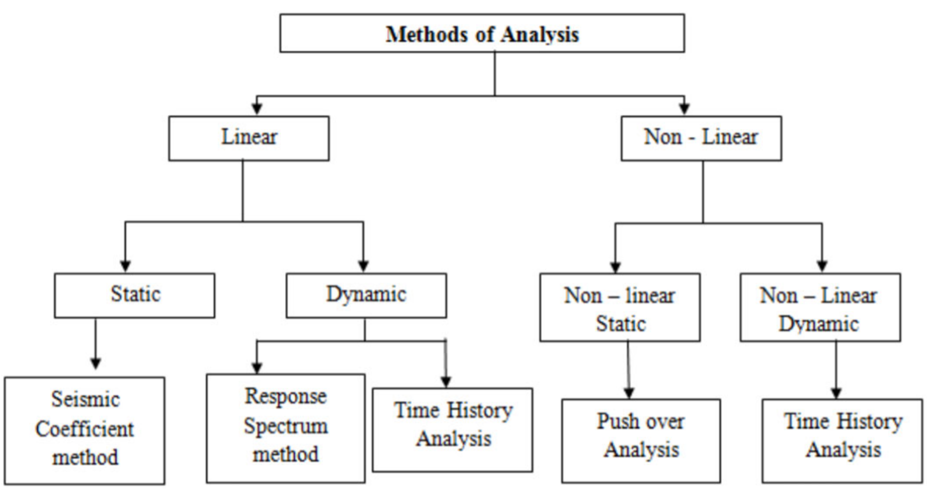

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Course Title: Existing Buildings Track 3 Nonlinear Analyses Procedures

- **Course Topics:**

1. The steps in Nonlinear Analyses Procedures.
2. The limitations of Nonlinear analysis methods.
3. Modelling of deformation-controlled parameters for Nonlinear analyses.
4. Modelling of force-controlled parameters for Nonlinear analyses.
5. Target displacement estimation formula and its coefficients.
6. The acceptance criteria for Nonlinear analysis.

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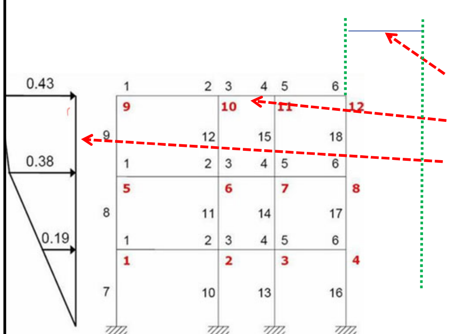
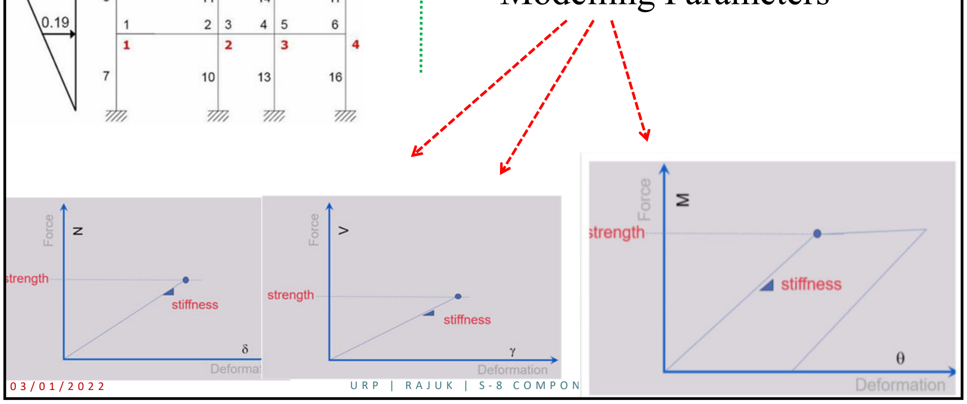
Static Nonlinear (Pushover) Analysis Inputs:



- Target Displacement
- Control Point
- Load Pattern
- Modelling Parameters



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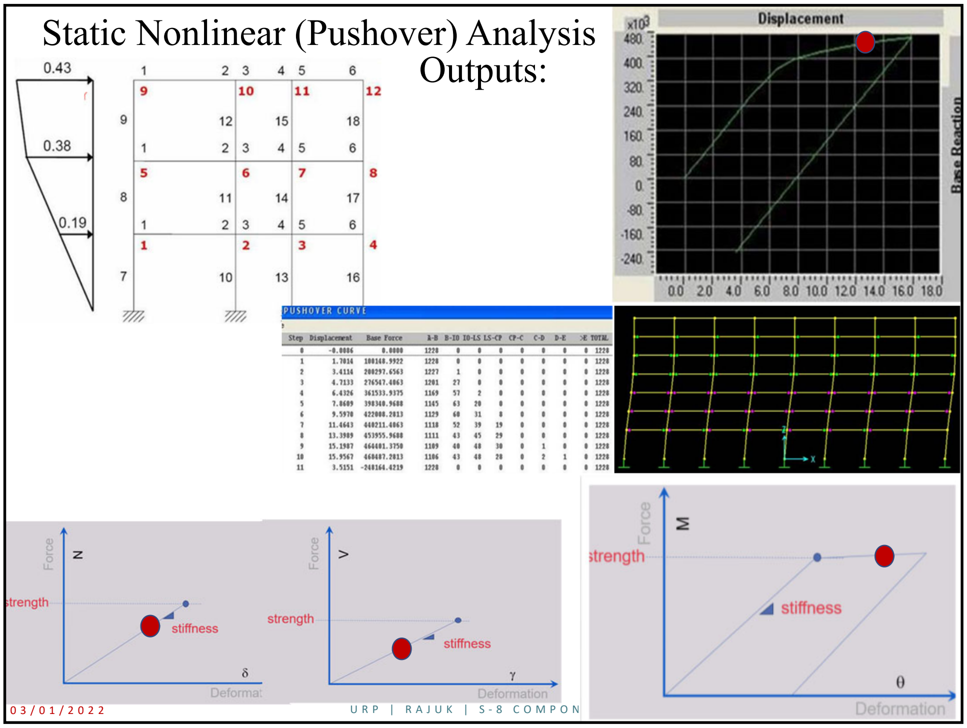
Static Nonlinear (Pushover) Analysis Outputs:



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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

		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)
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

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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Target Displacement

$$\delta_t = C_0 C_1 C_2 S_a \frac{T_e^2}{4\pi^2} g$$

C_0 = Modification factor to relate spectral displacement of an equivalent single-degree-of-freedom (SDOF) system to the roof displacement of the building multiple-degree-of-freedom (MDOF) system.

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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Target Displacement

$$\delta_t = C_0 C_1 C_2 \boxed{S_a} \frac{T_e^2}{4\pi^2} g$$

Probability of Exceedance	Mean Return Period (years)
50%/30 years	43
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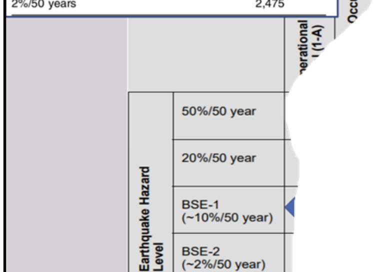

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Table 6.2.16: Site Dependent Soil Factor and Other Parameters Defining Elastic Response Spectrum

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

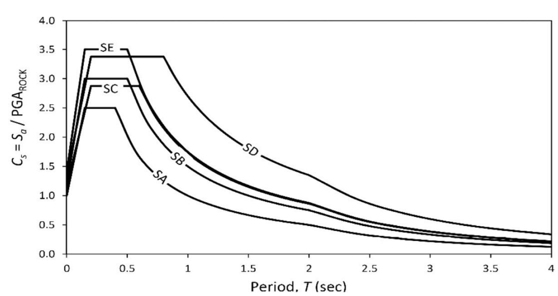

Figure 6.2.26 Normalized design acceleration response spectrum for different site classes.

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

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Target Displacement

$$\delta_t = C_0 C_1 C_2 \boxed{S_a \frac{T_e^2}{4\pi^2} g}$$

$$\text{Displacement} = y = A \sin \frac{2\pi}{T} t \quad = A \sin \omega t$$

$$\text{Velocity} \quad = \dot{y} = \frac{2\pi A}{T} \cos \frac{2\pi}{T} t = \omega A \cos \omega t$$

$$\text{Acceleration} \quad = \ddot{y} = \frac{4\pi^2 A}{-T^2} \sin \frac{2\pi}{T} t = -\omega^2 A \sin \omega t = -\omega^2 y$$

- Peak spectral acceleration, A, is related to peak spectral displacement, D, by the equation:

$$A = \omega_n^2 D = \left(\frac{2\pi}{T_n}\right)^2 D$$

$$S_a \rightarrow S_d$$

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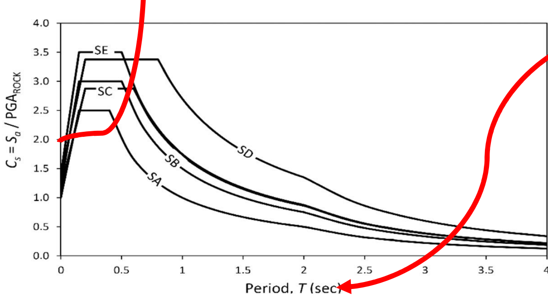
Target Displacement

$$\delta_t = C_0 C_1 C_2 \boxed{S_a} \frac{\boxed{T_e^2}}{4\pi^2} g$$

$$T_e = T_i \sqrt{\frac{K_i}{K_e}}$$



$$\boxed{T = 2\pi\sqrt{\frac{m}{k}}}$$

$$T_i = 2\pi\sqrt{\frac{m}{k_i}}$$

$$T_e = 2\pi\sqrt{\frac{m}{k_e}}$$

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Target Displacement

$$\delta_t = C_0 C_1 C_2 \boxed{S_a} \frac{\boxed{T_e^2}}{4\pi^2} g$$

$$T_e = T_i \sqrt{\frac{K_i}{K_e}}$$

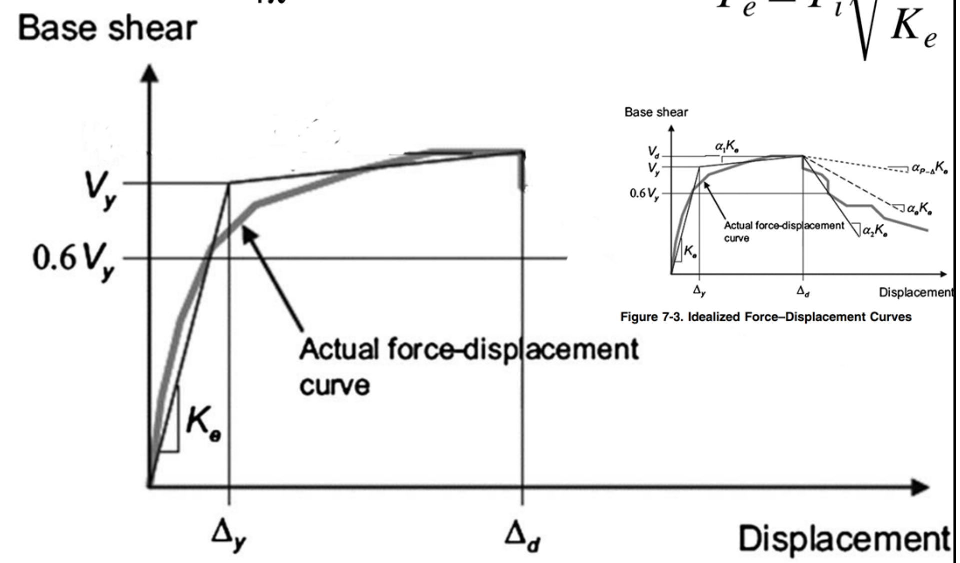

Figure 7-3. Idealized Force–Displacement Curves

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Target Displacement

$$\delta_t = \boxed{C_0} C_1 C_2 S_a \frac{T_e^2}{4\pi^2} g$$

C_0 = Modification factor to relate spectral displacement of an equivalent single-degree-of-freedom (SDOF) system to the roof displacement of the building multiple-degree-of-freedom (MDOF) system.

Table 7-5. Values for Modification Factor C_0

	Shear Buildings[a]		Other Buildings
Number of Stories	Triangular Load Pattern (1.1, 1.2, 1.3)	Uniform Load Pattern (2.1)	Any Load Pattern
1	1.0	1.0	1.0
2	1.2	1.15	1.2
3	1.2	1.2	1.3
5	1.3	1.2	1.4
10+	1.3	1.2	1.5

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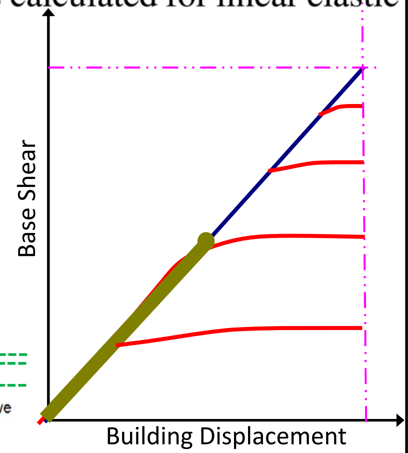
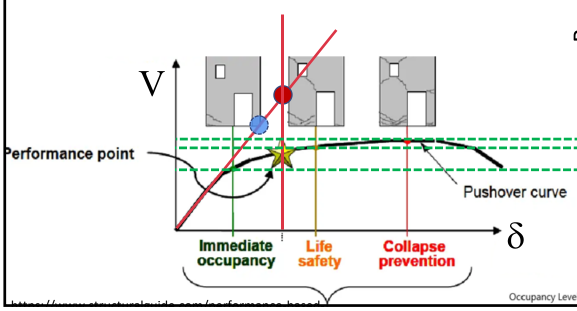
Target Displacement

$$\delta_t = C_0 \boxed{C_1} C_2 S_a \frac{T_e^2}{4\pi^2} g$$

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

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





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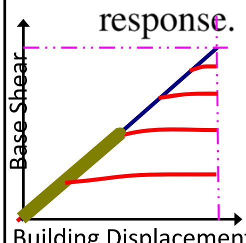
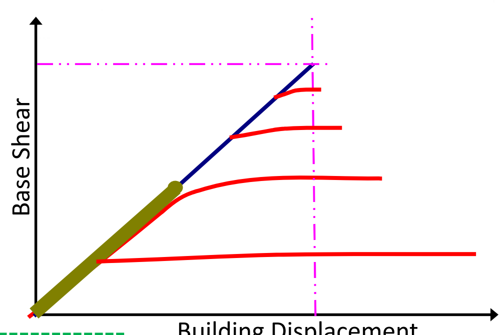
Target Displacement

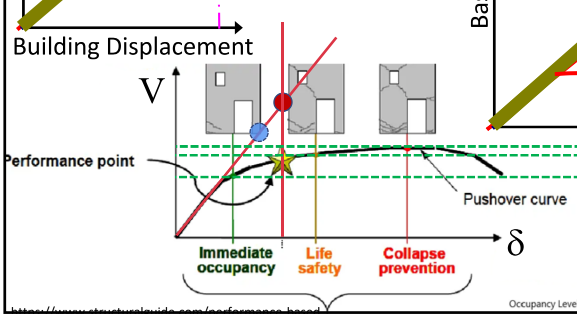
$$\delta_t = C_0 \boxed{C_1} C_2 S_a \frac{T_e^2}{4\pi^2} g$$

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

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







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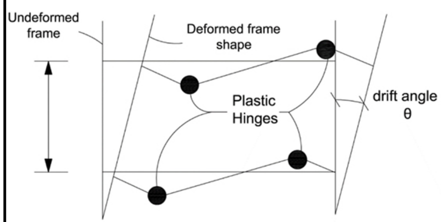
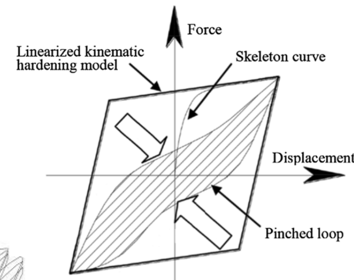
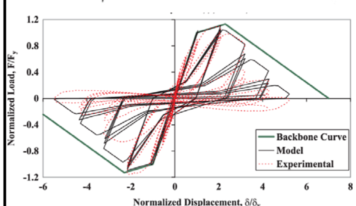
Target Displacement

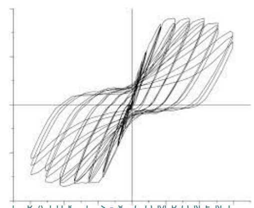
$$\delta_t = C_0 C_1 \boxed{C_2} S_a \frac{T_e^2}{4\pi^2} g \qquad C_2 = 1 + \frac{1}{800}\left(\frac{\mu_{\text{strength}} - 1}{T_e}\right)^2$$

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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Target Displacement

A modification factor relating expected maximum inelastic displacements to displacements calculated for linear elastic response

A factor to relate the spectral displacement of the equivalent SDF and building roof displacement

The effective period of the building in the direction under consideration

Acceleration due to gravity, 9.81 m/sec²

Target Displacement ⟵ $\delta_T = C_0 C_1 C_2 S_a \frac{T_e^2}{4\pi^2} g$

A modification factor to represent the effect of hysteresis shape on the maximum displacement response

The spectral acceleration at the effective period and damping ratio of the building in the direction under consideration

https://link.springer.com/content/pdf/10.1007F978-3-319-61914-9_15.pdf

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The load combinations in Nonlinear Static Procedure

Gravity Loads

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

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

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

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

$$\delta_t = C_0 C_1 C_2 S_a \frac{T_e^2}{4\pi^2} g$$

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

$$Q_G = 0.9Q_D$$

$$Q_G = Q_D + Q_L + Q_S$$

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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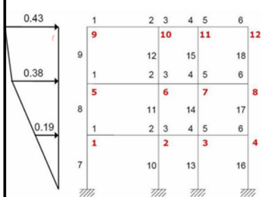
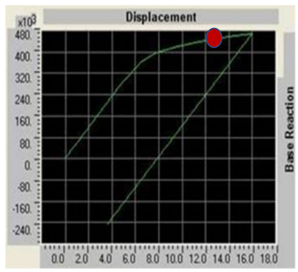
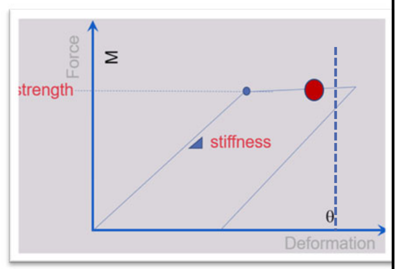
Acceptance Criteria for **Deformation-Controlled** actions

7.5.3.2.2 Acceptance Criteria for Deformation-Controlled Actions for NSP or NDP. Primary and secondary components shall have expected deformation capacities not less than maximum deformation demands calculated at target displacements. Primary and secondary component demands shall be within the acceptance criteria for nonlinear components at the selected Structural Performance Level.







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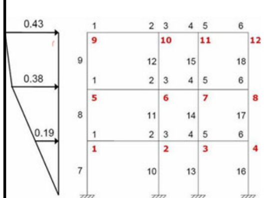
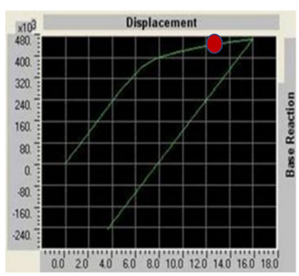
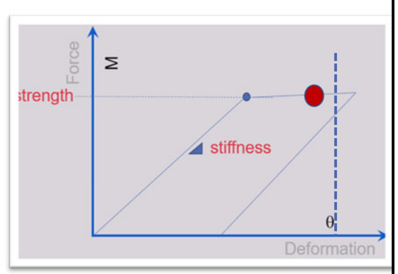
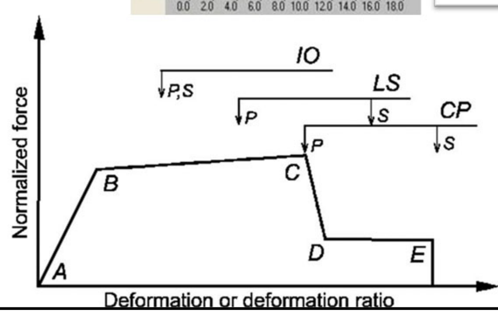
Acceptance Criteria for **Deformation-Controlled** actions

7.5.3.2.2 Acceptance Criteria for Deformation-Controlled Actions for NSP or NDP.









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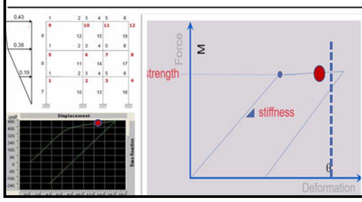
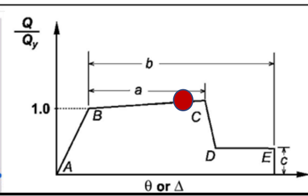
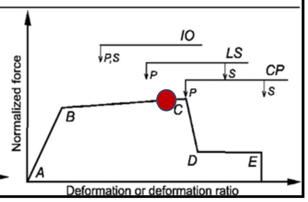
Acceptance Criteria for **Deformation-Controlled** actions

Table 10-7. Modeling Parameters and Numerical Acceptance Criteria for Nonlinear Procedures—Reinforced Concrete Beams

			Modeling Parameters[a]			Acceptance Criteria[a]		
						Plastic Rotation Angle (radians)		
			Plastic Rotation Angle (radians)		Residual Strength Ratio	Performance Level		
Conditions			*a*	*b*	*c*	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)	0.025	0.05	0.2	0.010	0.025	0.05
≤0.0	C	≥6 (0.5)	0.02	0.04	0.2	0.005	0.02	0.04
≥0.5	C	≤3 (0.25)	0.02	0.03	0.2	0.005	0.02	0.03
≥0.5	C	≥6 (0.5)	0.015	0.02	0.2	0.005	0.015	0.02
≤0.0	NC	≤3 (0.25)	0.02	0.03	0.2	0.005	0.02	0.03
≤0.0	NC	≥6 (0.5)	0.01	0.015	0.2	0.0015	0.01	0.015
≥0.5	NC	≤3 (0.25)	0.01	0.015	0.2	0.005	0.01	0.015
≥0.5	NC	≥6 (0.5)	0.005	0.01	0.2	0.0015	0.005	0.01
Condition ii. Beams controlled by shear[b]								
Stirrup spacing ≤ *d*/2			0.0030	0.02	0.2	0.0015	0.01	0.02
Stirrup spacing > *d*/2			0.0030	0.01	0.2	0.0015	0.005	0.01
Condition iii. Beams controlled by inadequate development or splicing along the span[b]								
Stirrup spacing ≤ *d*/2			0.0030	0.02	0.0	0.0015	0.01	0.02
Stirrup spacing > *d*/2			0.0030	0.01	0.0	0.0015	0.005	0.01
Condition iv. Beams controlled by inadequate embedment into beam–column joint[b]								
			0.015	0.03	0.2	0.01	0.02	0.03







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Acceptance Criteria for **Force-Controlled** actions

7.5.3.2.3 Acceptance Criteria for Force-Controlled Actions for NSP or NDP. Force-controlled components that are not explicitly included in the mathematical model with nonlinear force-deformation properties per Section 7.5.1.2 shall satisfy:

$$\gamma\chi(Q_{UF} - Q_G) + Q_G \leq Q_{CL}$$

Q_{UF} = the force-controlled demand
Q_G = Gravity load demand
Q_{CL} = Lower-bound component strength
γ = Load factor obtained from Table 7-8:

Table 7-8. Load Factor for Force-Controlled Behaviors

Action Type	γ
Critical	1.3
Ordinary	1.0
Noncritical	1.0

χ is taken as 1.0 for Collapse Prevention or 1.3 for Life Safety and Immediate Occupancy.

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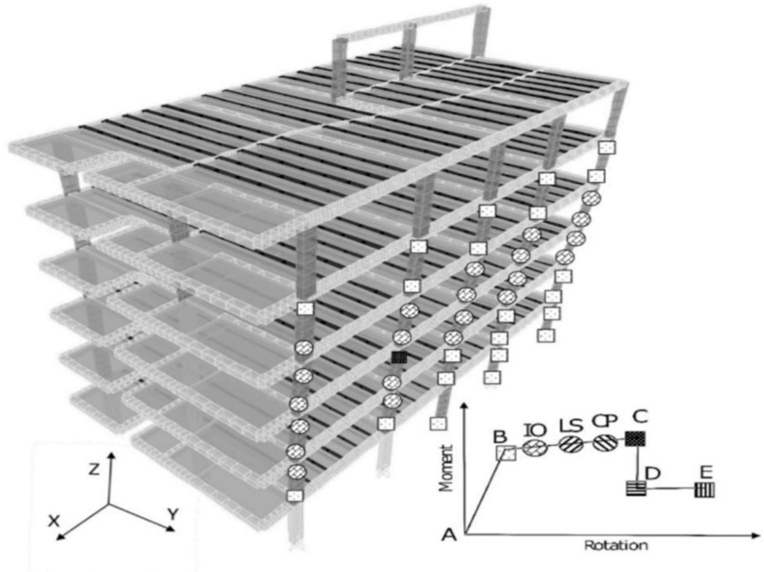

Building deformation after push-over lateral loads path along "Y" direction.

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Nonlinear Static Analysis

versus

Nonlinear Dynamic Analysis

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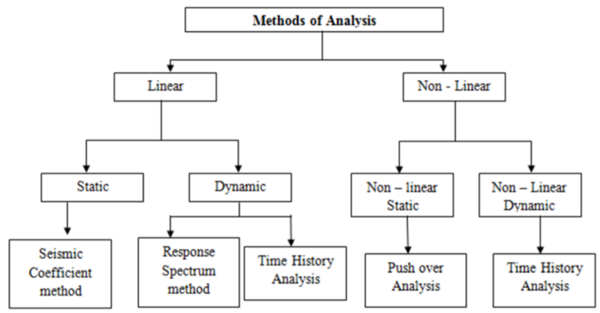
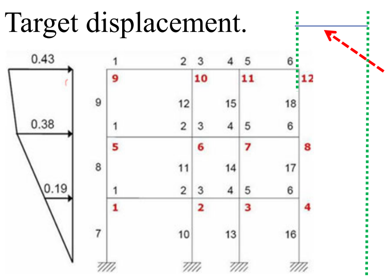
Summary 1/5

- Pushover analysis.



- Target displacement.



- Target Displacement

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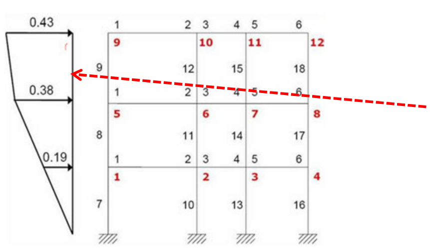
Summary 2/5

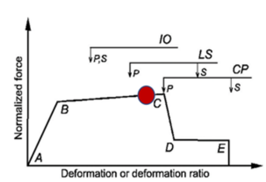
- Load Pattern in the Pushover Analysis?



- Load Pattern

- Acceptance Criteria for "Deformation-Controlled actions" in nonlinear analysis.

Deformation capacity $\geq$ Deformation Demand



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Summary 3/5

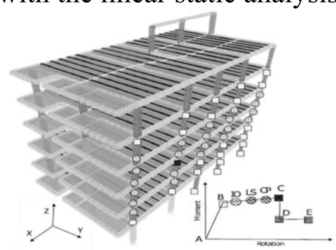
• Acceptance Criteria for "Force-Controlled actions" in nonlinear analysis.

Lower-bound strength $\geq$ Force Demand

$$\gamma\chi(Q_{UF} - Q_G) + Q_G \leq Q_{CL}$$

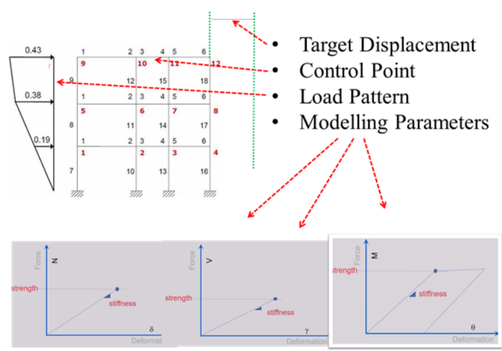
• The main difference of pushover with the linear static analysis.

Effects of damages are considered



Summary 4/5

• Inputs in pushover analysis.

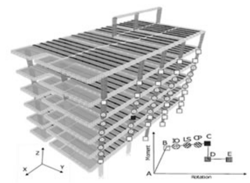


• If a "Force-Controlled action", does not satisfy the acceptance criteria, what is the building performance level?

Summary 5/5

- In linear analysis the load combinations for “load-controlled” and “deformation-controlled actions” are different. Why in nonlinear analysis they are the same?

Effects of damages are considered



- Why nonlinear dynamic analysis has not been the preferred approach of analysis yet?

What will be the characteristics of the next earthquake? How to select the earthquake records?

Course Title: Existing Buildings Track 3 Nonlinear Analyses Procedures

- **Course Outcomes:**

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

Questions?
Thank you

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