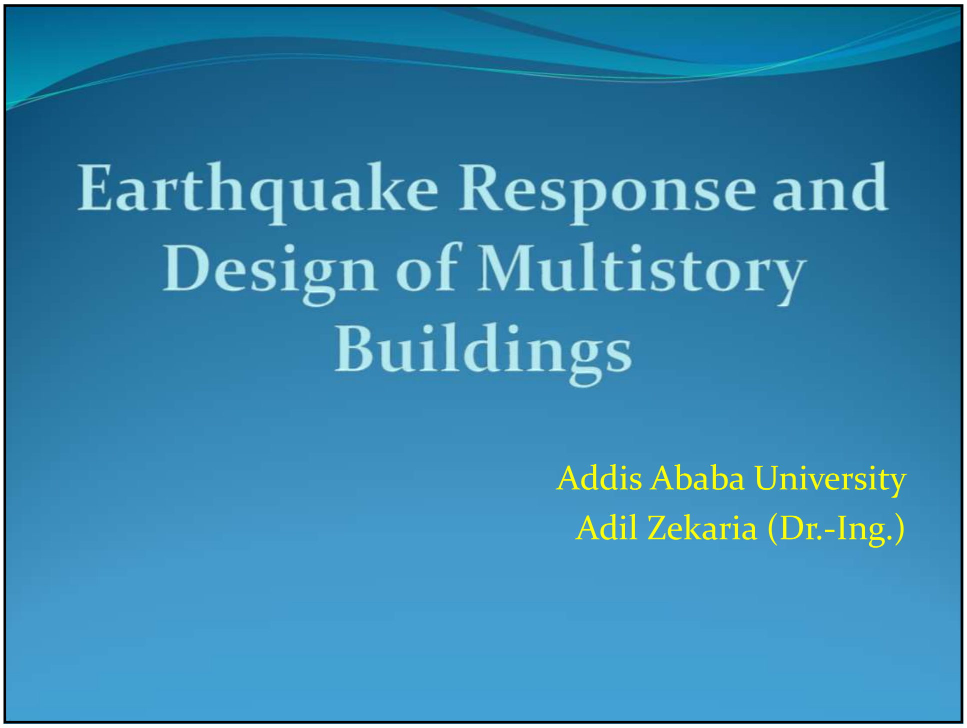

Earthquake Response and Design of Multistory Buildings

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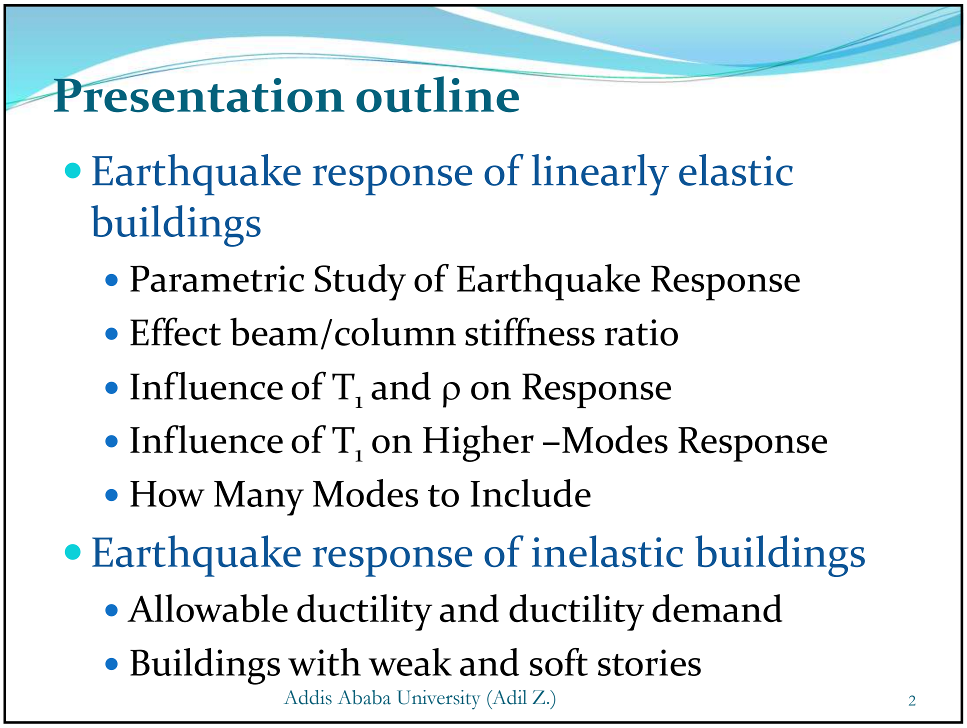
Adil Zekaria (Dr.-Ing.)



Presentation outline

- Earthquake response of linearly elastic buildings
  - Parametric Study of Earthquake Response
  - Effect beam/column stiffness ratio
  - Influence of T_1 and ρ on Response
  - Influence of T_1 on Higher –Modes Response
  - How Many Modes to Include
- Earthquake response of inelastic buildings
  - Allowable ductility and ductility demand
  - Buildings with weak and soft stories

Earthquake response of linearly elastic buildings

Earthquake response of linearly elastic buildings

- In the 4th chapter (Chopra ch. 13) RHA and RSA were discussed for linearly elastic system with finite DOF.
- In this section, the effect of fundamental period and beam to column stiffness ratio will be discussed
- This discussion will help us understand:
    - How these parameters affect the response of buildings
    - How they affect the relative response contribution of the different modes
    - The condition under which the first mode or the first two modes are sufficient
    - Significance of higher modes in building response

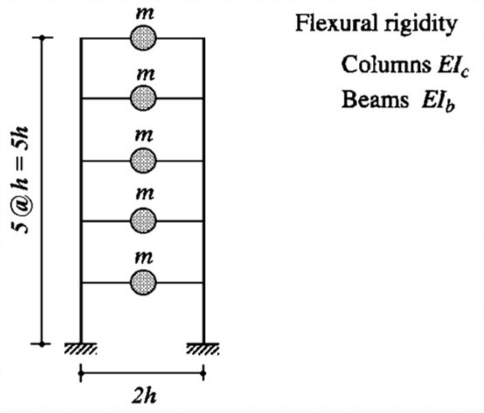
Earthquake response of linearly elastic buildings

- Parametric Study of Earthquake Response

- Key parameters
  - Fundamental natural vibration period, T_1
  - Beam to column stiffness ratio, ρ

$$\rho = \frac{\sum_{beams} EI_b / L_b}{\sum_{columns} EI_c / L_c}$$

Effect of beam/column stiffness ratio, ρ

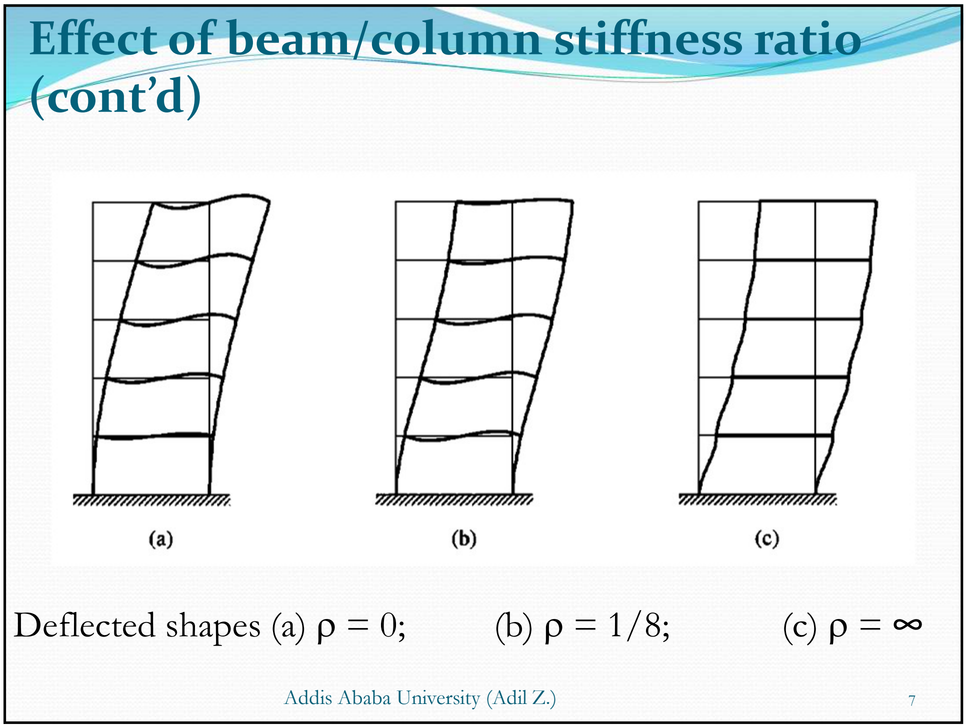


- System Analyzed

$$\rho = \frac{I_b}{4I_c}$$

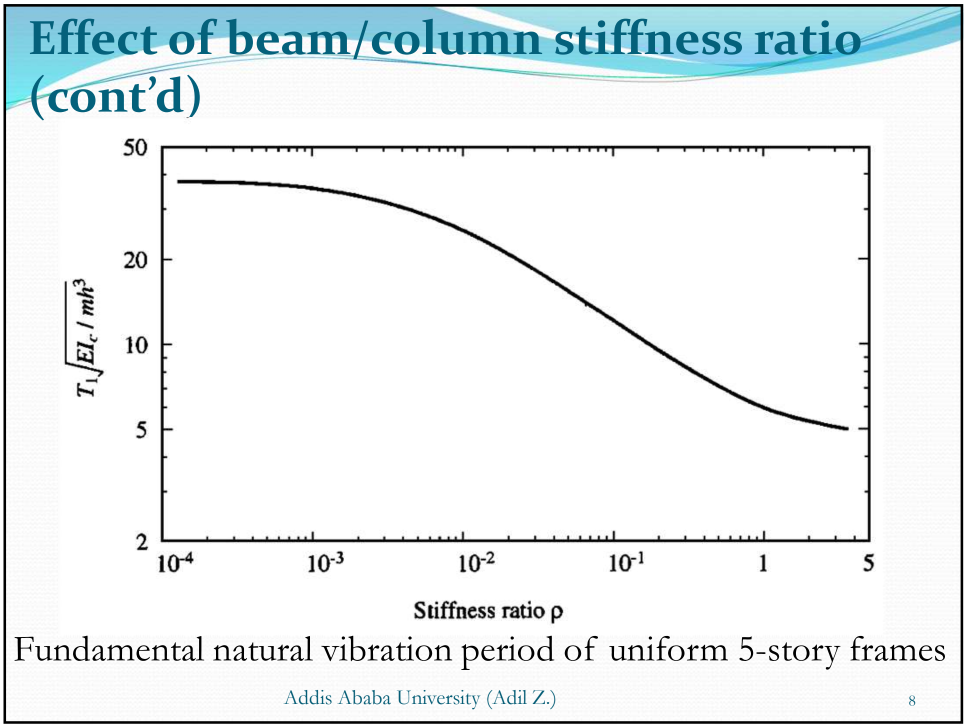
- ρ controls:
  - fundamental periods
  - closeness/separation of natural periods
  - shapes of natural modes

Properties of uniform 5-story frames



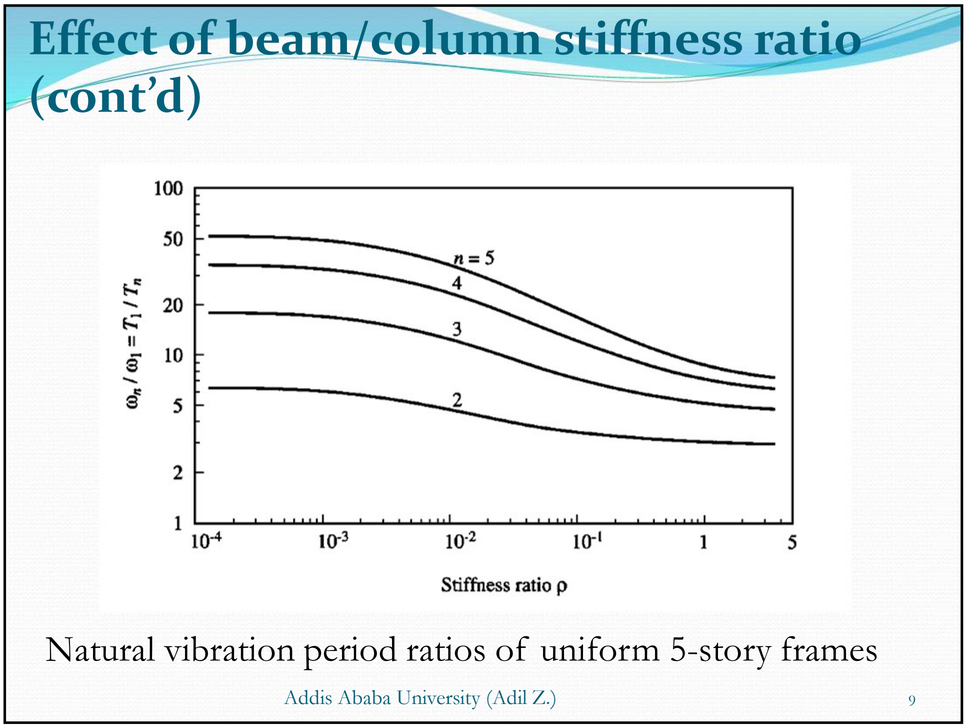
Effect of beam/column stiffness ratio (cont'd)

Deflected shapes (a) ρ = 0; (b) ρ = 1/8; (c) ρ = ∞



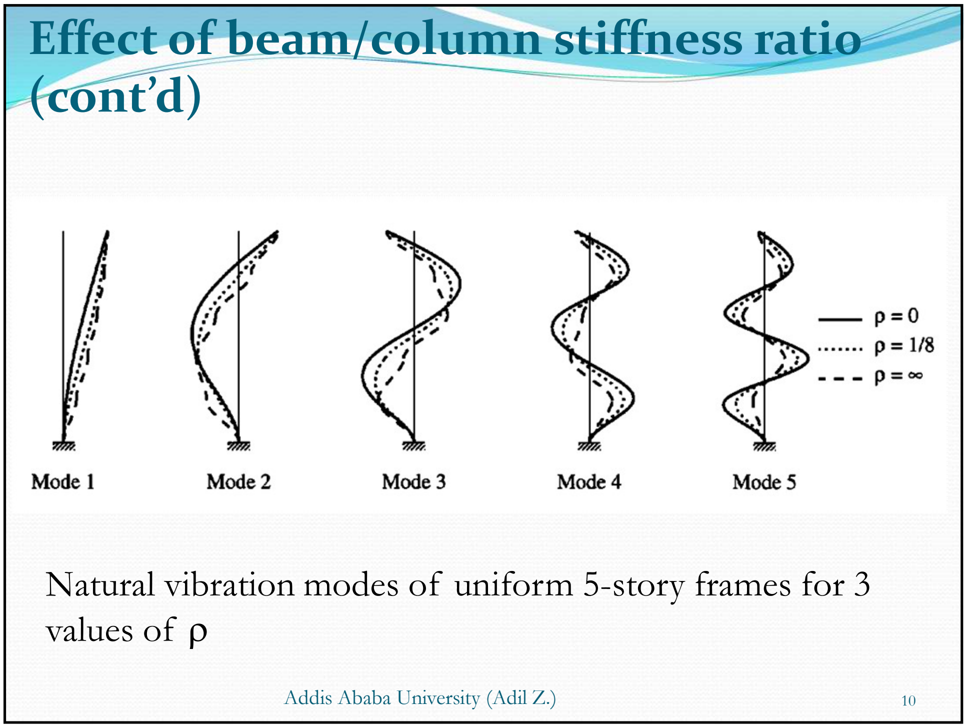
Effect of beam/column stiffness ratio (cont'd)

Fundamental natural vibration period of uniform 5-story frames



Effect of beam/column stiffness ratio (cont'd)

Natural vibration period ratios of uniform 5-story frames



Effect of beam/column stiffness ratio (cont'd)

Natural vibration modes of uniform 5-story frames for 3 values of ρ

Effect of beam/column stiffness ratio (cont'd)

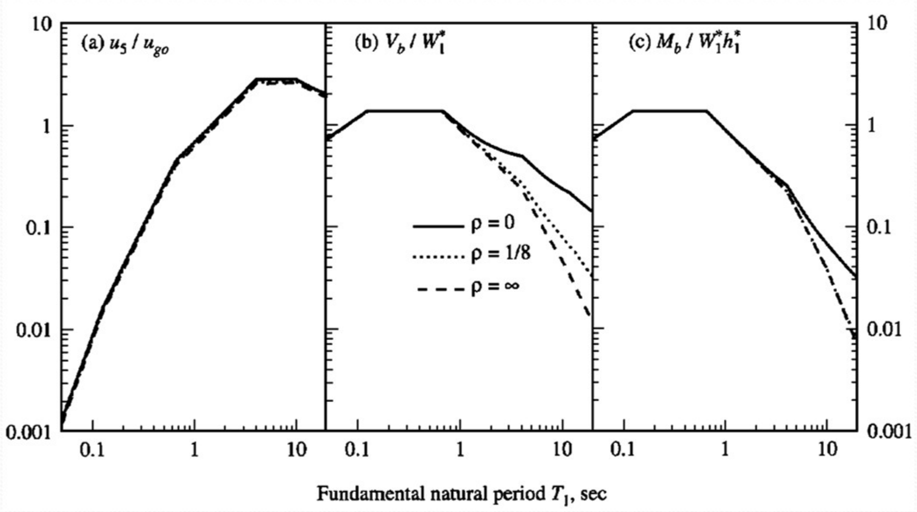
Fundamental mode properties for 3 values of ρ

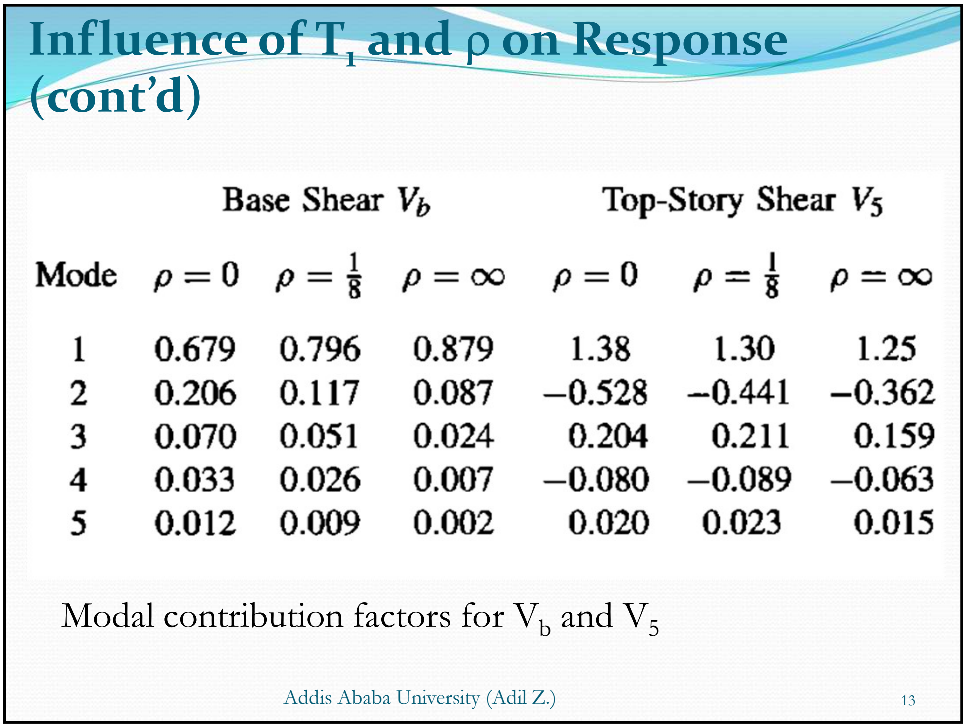
	ρ = **0**	ρ = **1/8**	ρ = ∞
W_1*/W	0.679	0.796	0.880
h_1*/5h	0.794	0.742	0.703

Where:

W1* - Effective modal weight of the fundamental mode
h1* - Effective modal height of the fundamental mode

Influence of T_1 and ρ on Response

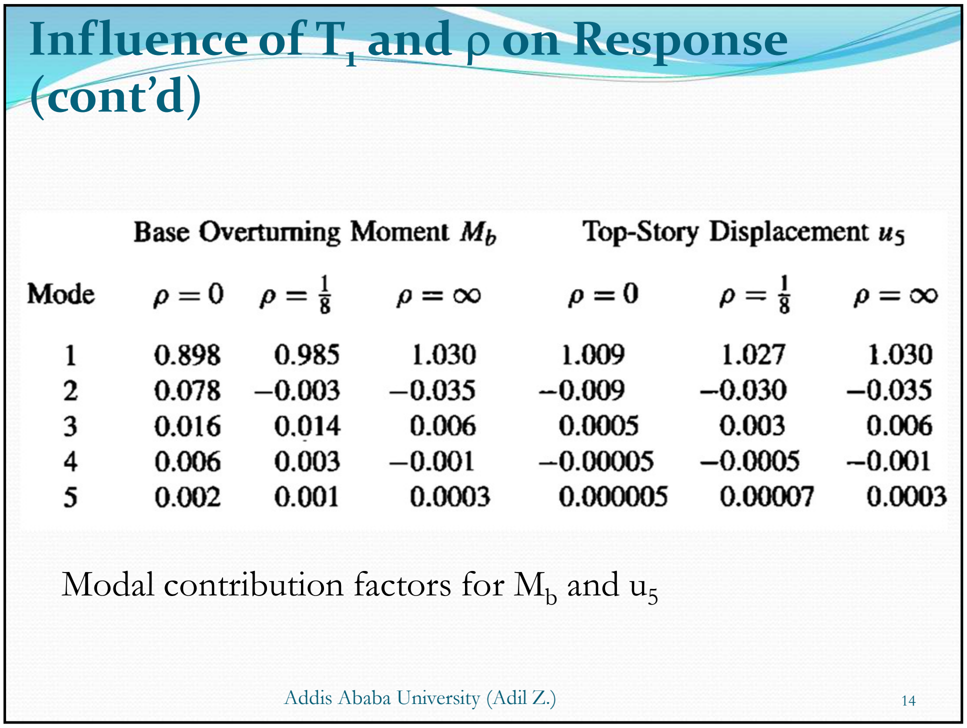




Influence of T_1 and ρ on Response (cont'd)

	Base Shear V_b			Top-Story Shear V_5		
Mode	$\rho = 0$	$\rho = \frac{1}{8}$	$\rho = \infty$	$\rho = 0$	$\rho = \frac{1}{8}$	$\rho = \infty$
1	0.679	0.796	0.879	1.38	1.30	1.25
2	0.206	0.117	0.087	−0.528	−0.441	−0.362
3	0.070	0.051	0.024	0.204	0.211	0.159
4	0.033	0.026	0.007	−0.080	−0.089	−0.063
5	0.012	0.009	0.002	0.020	0.023	0.015

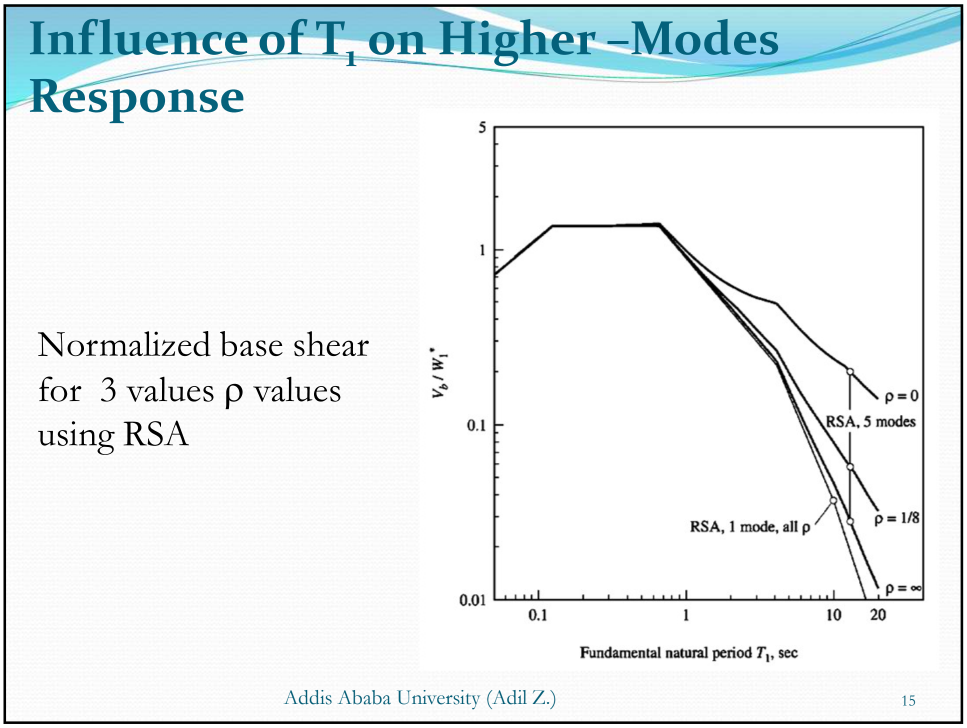
Modal contribution factors for V_b and V_5



Influence of T_1 and ρ on Response (cont'd)

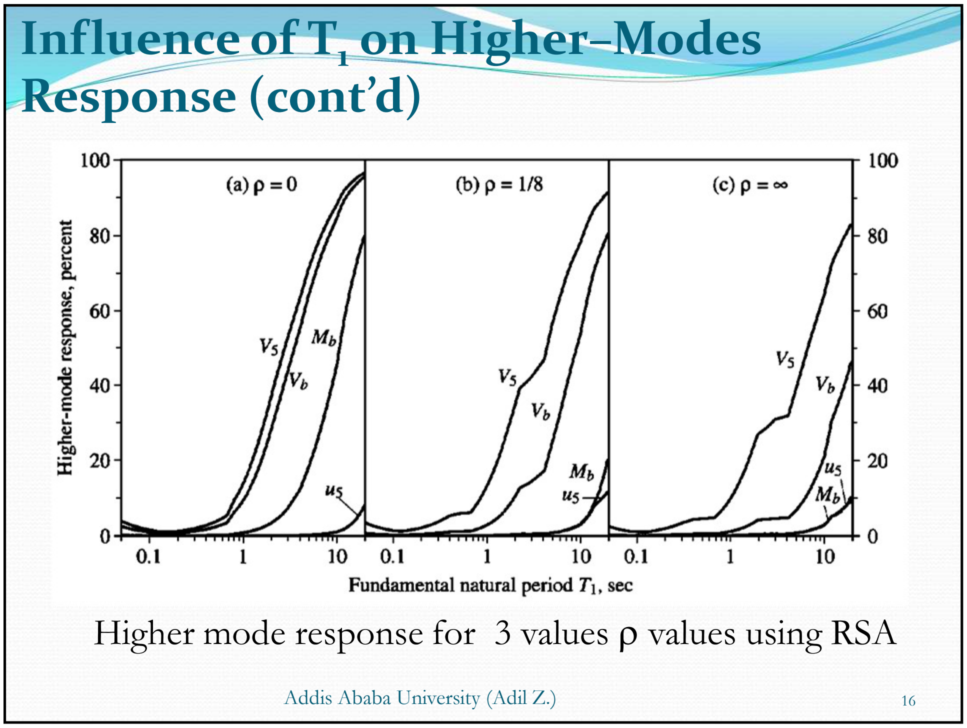
	Base Overturning Moment M_b			Top-Story Displacement u_5		
Mode	$\rho = 0$	$\rho = \frac{1}{8}$	$\rho = \infty$	$\rho = 0$	$\rho = \frac{1}{8}$	$\rho = \infty$
1	0.898	0.985	1.030	1.009	1.027	1.030
2	0.078	−0.003	−0.035	−0.009	−0.030	−0.035
3	0.016	0.014	0.006	0.0005	0.003	0.006
4	0.006	0.003	−0.001	−0.00005	−0.0005	−0.001
5	0.002	0.001	0.0003	0.000005	0.00007	0.0003

Modal contribution factors for M_b and u_5



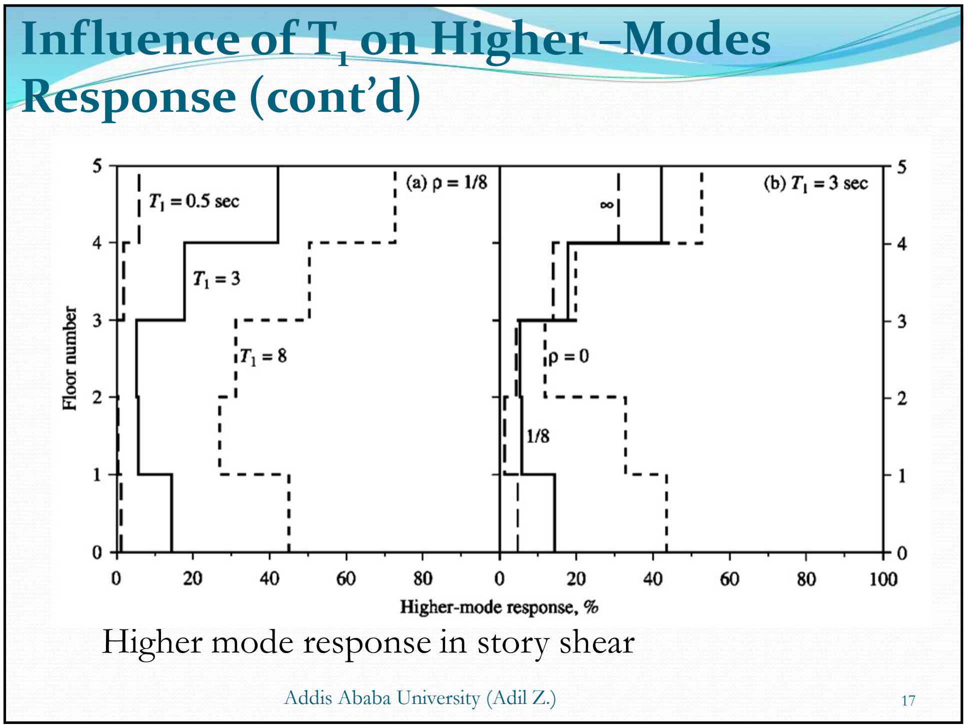
Influence of T_1 on Higher –Modes Response

Normalized base shear for 3 values ρ values using RSA



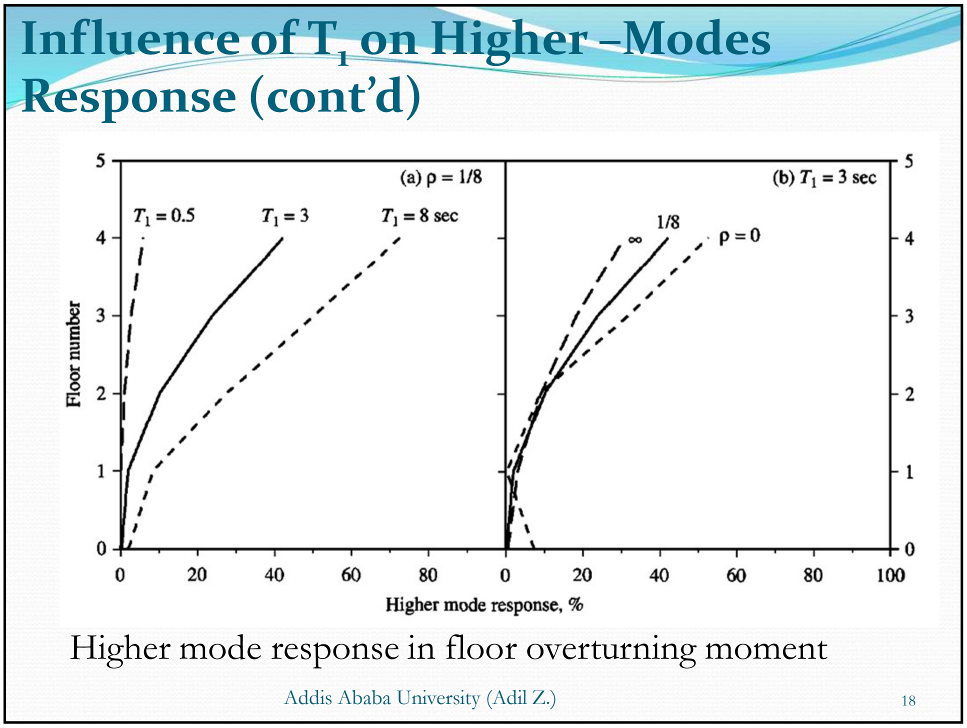
Influence of T_1 on Higher–Modes Response (cont'd)

Higher mode response for 3 values ρ values using RSA



Influence of T_1 on Higher –Modes Response (cont'd)

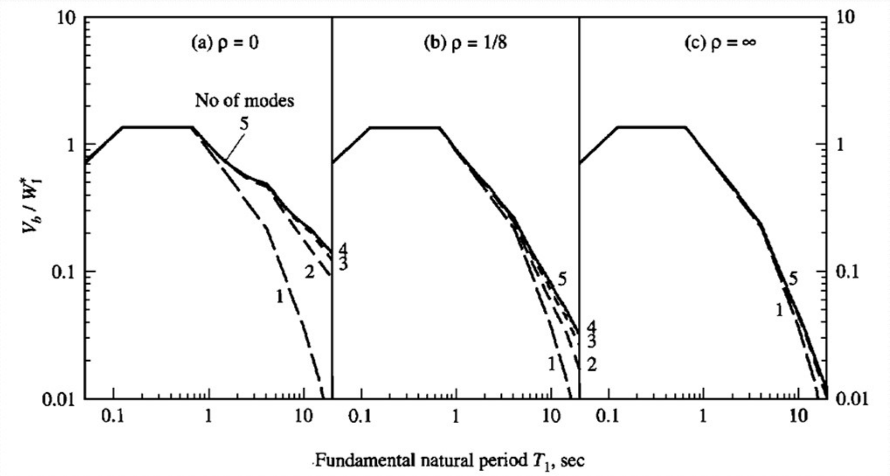
Higher mode response in story shear



Influence of T_1 on Higher –Modes Response (cont'd)

Higher mode response in floor overturning moment

How Many Modes to Include



Normal base shear using RSA considering 1, 2, 3, 4, or 5 modes

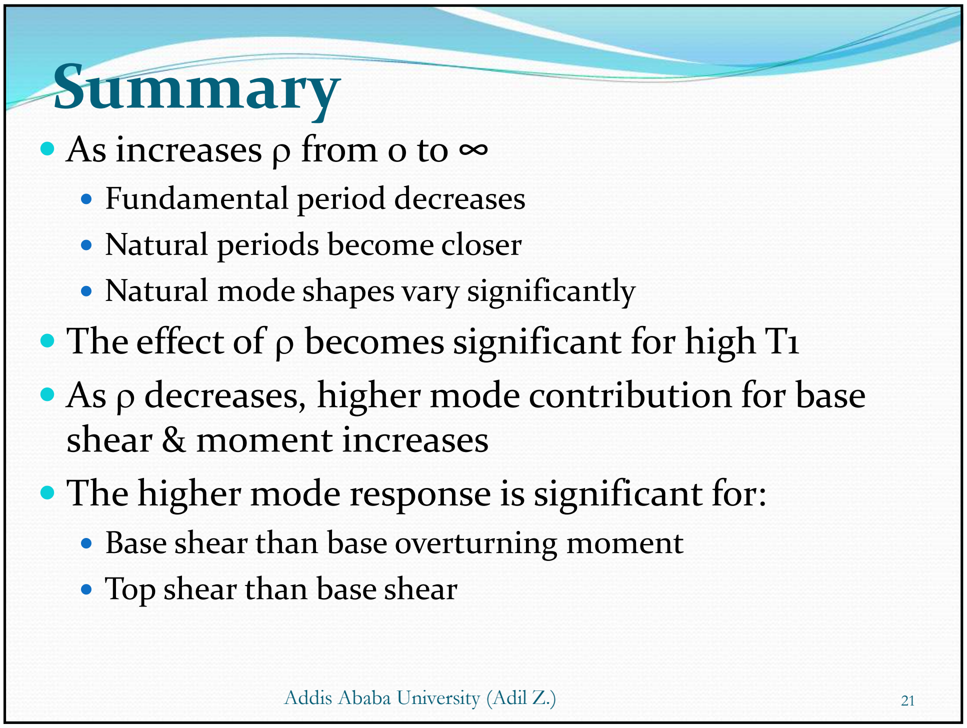
How Many Modes to Include (Cont'd)

Mode number J should be chosen so that the error e_J is sufficiently small

$$e_J = 1 - \sum_{n=1}^{J} \bar{r}_n$$

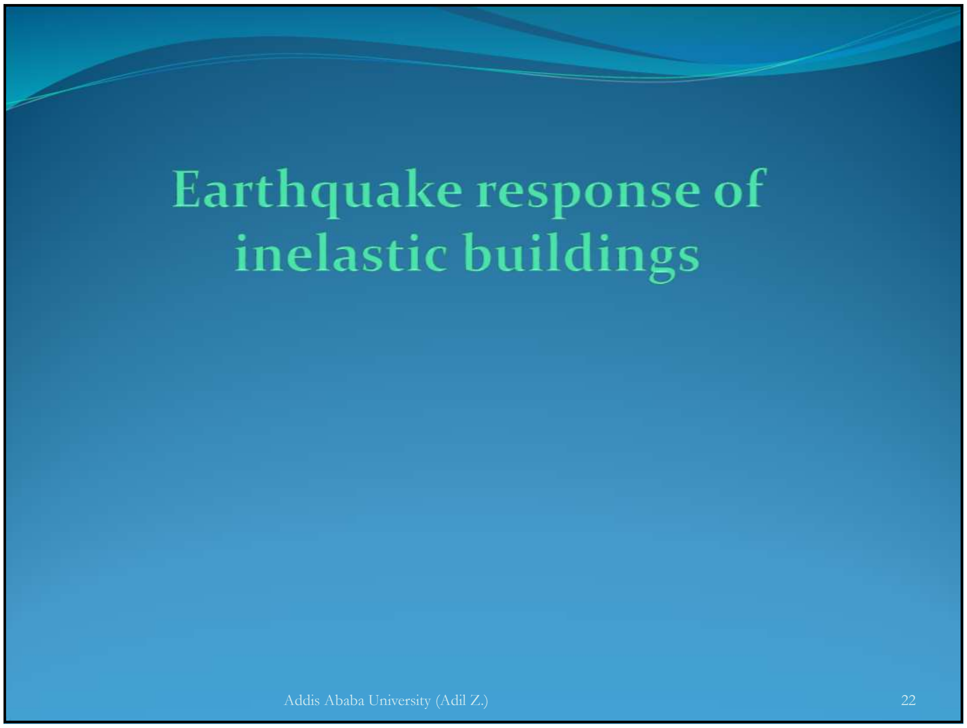
For example:
If only two modes are selected the error e_2

Response	$\rho = 0$	$\rho = \frac{1}{8}$	$\rho = \infty$
V_5	0.144	0.144	0.110
V_b	0.115	0.086	0.033
M_b	0.024	0.018	0.005
u_5	0.0004	0.003	0.005



Summary

- As increases ρ from 0 to ∞
  - Fundamental period decreases
  - Natural periods become closer
  - Natural mode shapes vary significantly
- The effect of ρ becomes significant for high T1
- As ρ decreases, higher mode contribution for base shear & moment increases
- The higher mode response is significant for:
  - Base shear than base overturning moment
  - Top shear than base shear



Earthquake response of inelastic buildings

Earthquake response of inelastic buildings

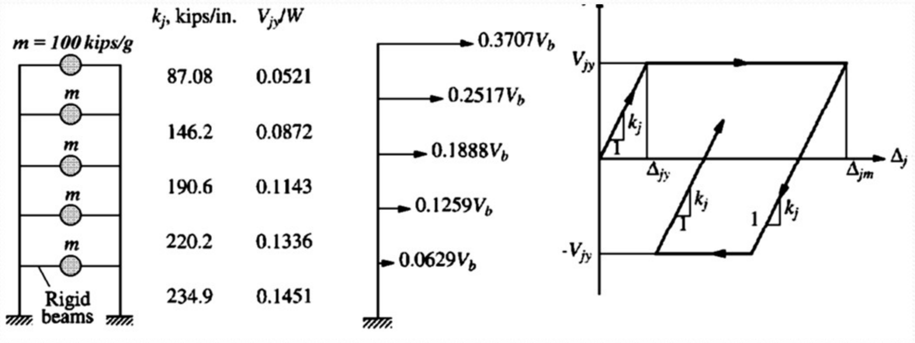
- As mentioned in the 3rd chapter (Chopra ch. 7) most building are expected to deform in to their inelastic range when subjected to ground shaking (it is of central importance in earthquake engineering)
- For a SDOF systems, the ductility demand imposed by an EQ motion on the system designed will be exactly equak to the allowable ductility. Such exact correspondence between ductility demand and allowable ductility always exist for SDOF system when the yield strength f_y is determined from the EQ response spectrum corresponding to the allowable ductility.
- This is not true for MDOF system as to be demonstrated next

Earthquake response of inelastic buildings

- For MDOF systems
  - Ductility demand depends on the relative yield strengths of the various stories, in some cases:

    ductility demand >> allowable ductility
  - Two extreme cases are discussed:
    - Weak first story :– smaller yield strength
    - Soft first story :– smaller yield strength & smaller stiffness
  - Consider a five story shear frame with elastoplastic relation between shear force V_j and story drift Δ_j

Uniform five story shear standard frame

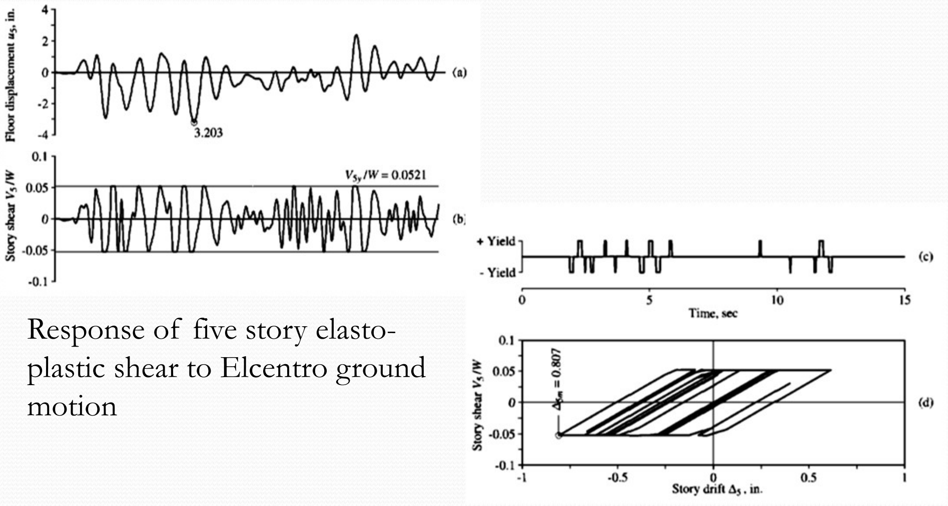


(a) system properties; (b) code forces; (c) elastoplastic relation

Uniform five story shear standard frame

- The initial, linearly elastic values of story stiffnesses, k_j, are determined by satisfying two requirements:
  - The fundamental period is $T_1 = 0.8$ s for the system with equal floor masses (based on periods of five story steel MRF buildings determined from their motions recorded during earthquakes)
  - Static application of UBC94 code forces, assuming the structure to be linearly elastic, should cause equal drift in all five stories, resulting in floor deflections increasing linearly with height.
- The story yield strengths, V_{jy} are determined from response spectrum for elastoplastic SDOF system corresponding to an allowable ductility of $\mu = 4$.

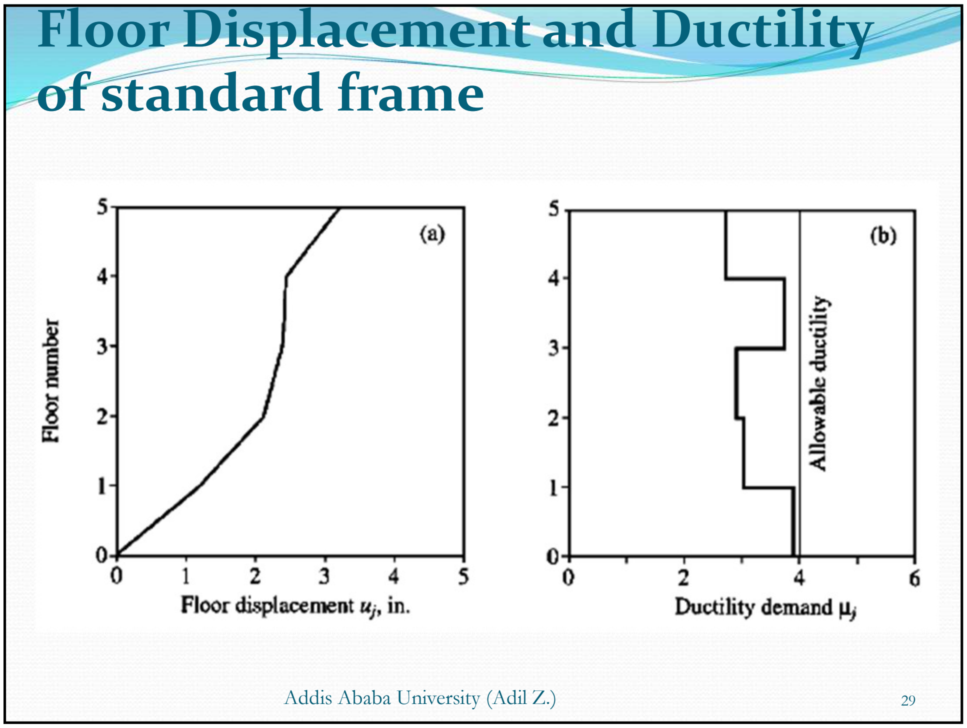
Uniform five story shear standard frame: response to Elcentro EQ



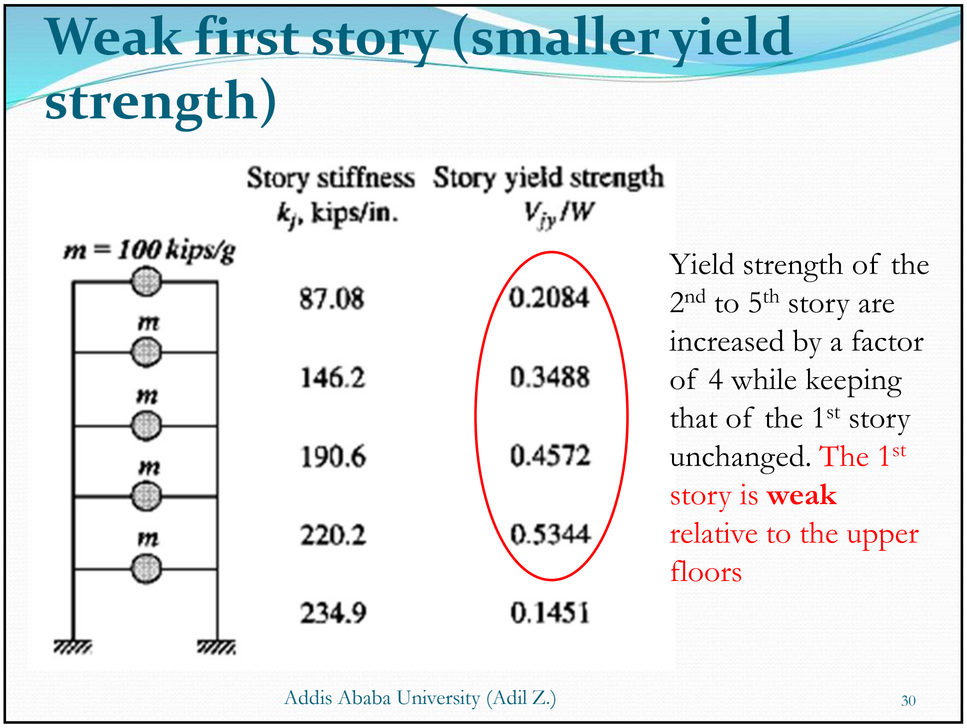
Response of five story elasto-plastic shear to Elcentro ground motion

Uniform five story shear standard frame: response to Elcentro EQ

- The story ductility demand for multistory building vary over its height and differ from the allowable ductility used in defining the design spectrum and computing the story yield strengths. This is clearly seen in the *next slide*.
- These are the limitations of the design procedure wherein story yield strengths are determined by liner analysis of the system using inelastic response (design) spectrum corresponding to the allowable ductility. Thus a different approach to inelastic structural design is necessary so that the ductility demands remain within the allowable ductility.



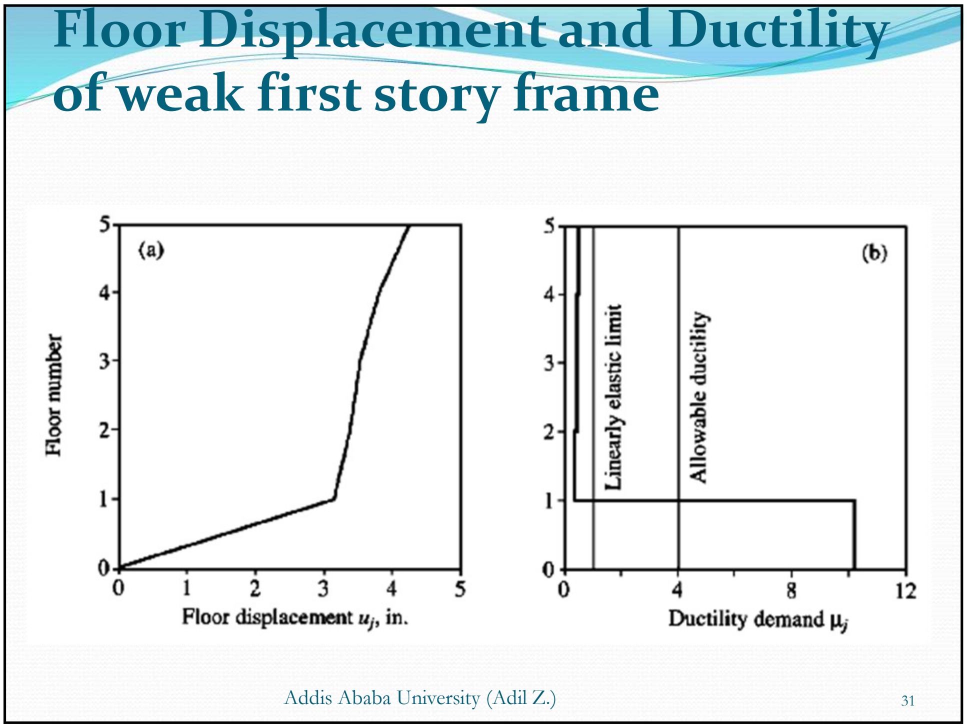
Floor Displacement and Ductility of standard frame



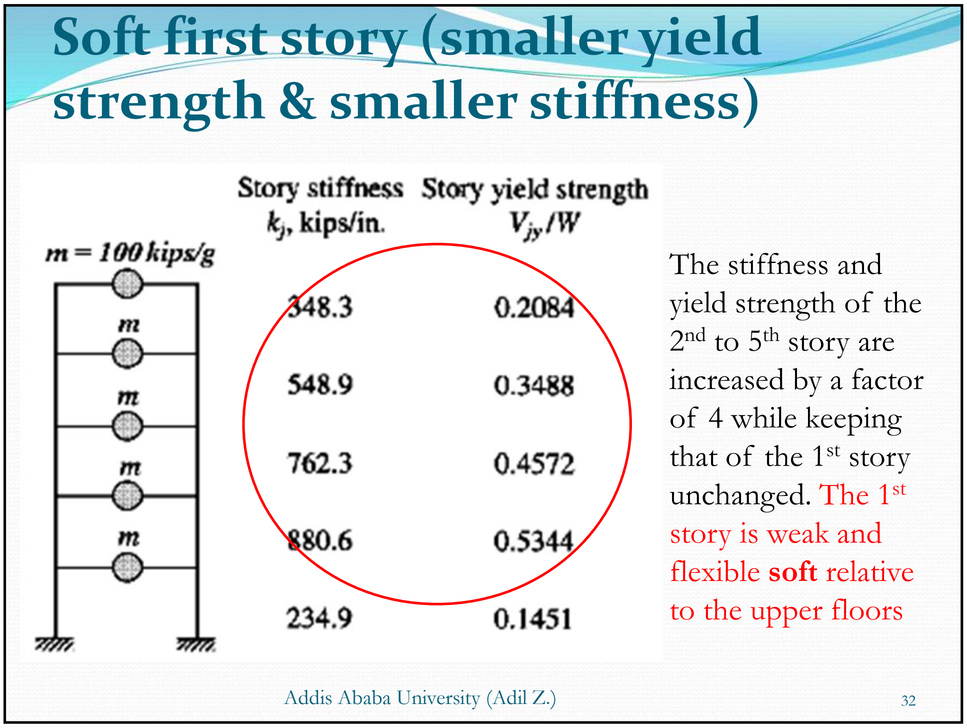
Weak first story (smaller yield strength)

Story stiffness k_j, kips/in.	Story yield strength V_{jy}/W
87.08	0.2084
146.2	0.3488
190.6	0.4572
220.2	0.5344
234.9	0.1451

Yield strength of the 2nd to 5th story are increased by a factor of 4 while keeping that of the 1st story unchanged. The 1st story is **weak** relative to the upper floors



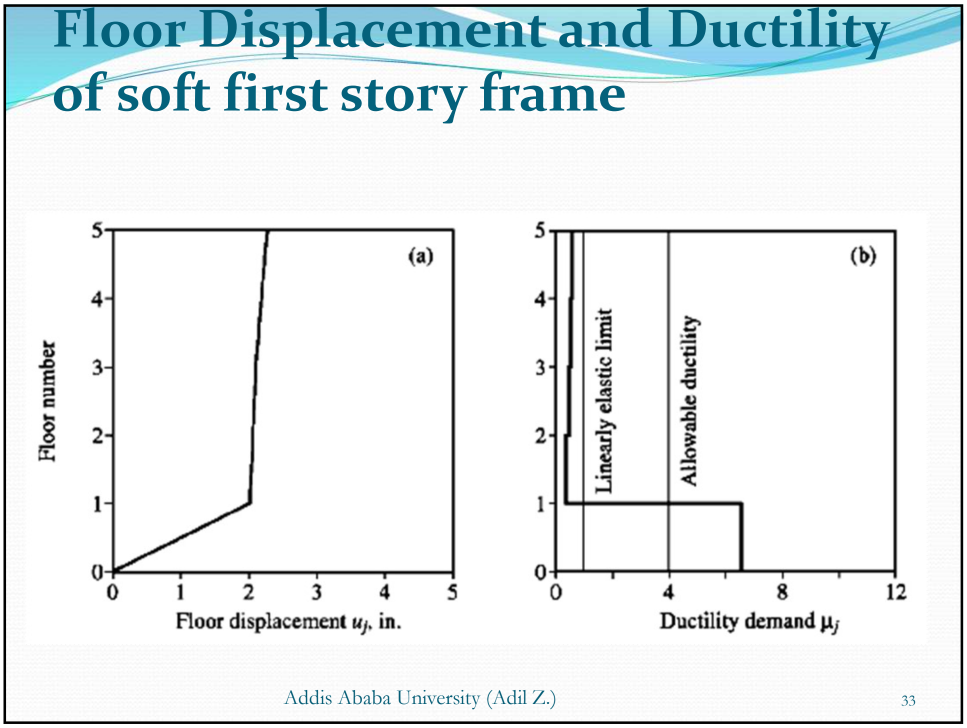
Floor Displacement and Ductility of weak first story frame



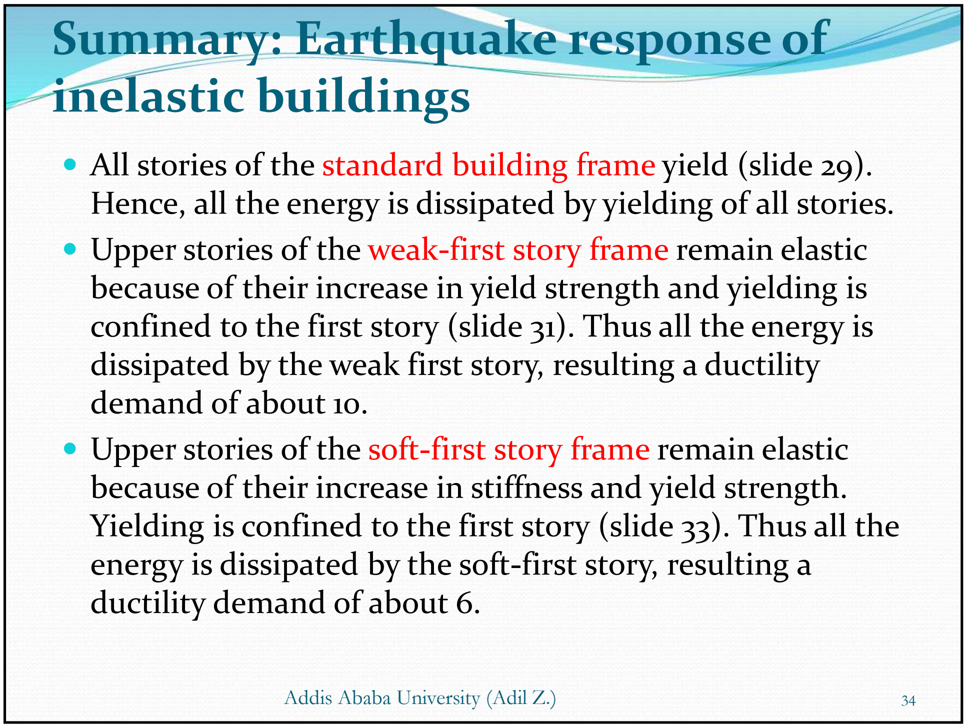
Soft first story (smaller yield strength & smaller stiffness)

Story stiffness k_j, kips/in.	Story yield strength V_{jy}/W
348.3	0.2084
548.9	0.3488
762.3	0.4572
880.6	0.5344
234.9	0.1451

The stiffness and yield strength of the 2nd to 5th story are increased by a factor of 4 while keeping that of the 1st story unchanged. The 1st story is weak and flexible **soft** relative to the upper floors



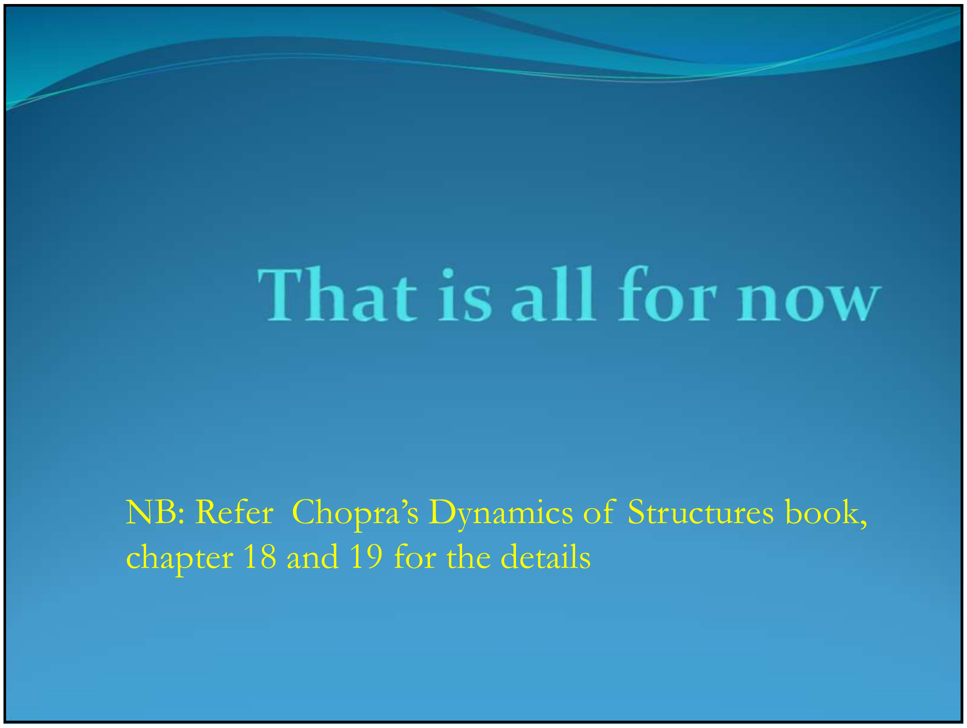
Floor Displacement and Ductility of soft first story frame



Summary: Earthquake response of inelastic buildings

- All stories of the standard building frame yield (slide 29). Hence, all the energy is dissipated by yielding of all stories.
- Upper stories of the weak-first story frame remain elastic because of their increase in yield strength and yielding is confined to the first story (slide 31). Thus all the energy is dissipated by the weak first story, resulting a ductility demand of about 10.
- Upper stories of the soft-first story frame remain elastic because of their increase in stiffness and yield strength. Yielding is confined to the first story (slide 33). Thus all the energy is dissipated by the soft-first story, resulting a ductility demand of about 6.

Soft first story buildings



That is all for now

NB: Refer Chopra's Dynamics of Structures book, chapter 18 and 19 for the details