The National Academies of
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TRANSPORTATION RESEARCH BOARD

TRB Webinar Program
Direct Displacement Based Seismic Design of Bridges

Thursday, June 22, 2017
2:00-3:30 PM ET

The Transportation Research Board has met the standards and requirements of the Registered Continuing Education Providers Program. Credit earned on completion of this program will be reported to RCEP. A certificate of completion will be issued to participants that have registered and attended the entire session. As such, it does not include content that may be deemed or construed to be an approval or endorsement by RCEP.

RCEP

REGISTERED CONTINUING EDUCATION PROGRAM

Purpose

Discuss the concepts of Direct Displacement-Based Seismic Design (DDBD) as a methodology suitable for seismic design of bridges.

Learning Objectives

At the end of this webinar, you will be able to:

- Understand the fundamentals of DDBD
- Apply DDBD principles do the design of simple bridges
- Understand the issues involved in developing more complex structures

TRB WEBINAR DISPLACEMENT-BASED SEISMIC DESIGN OF BRIDGES

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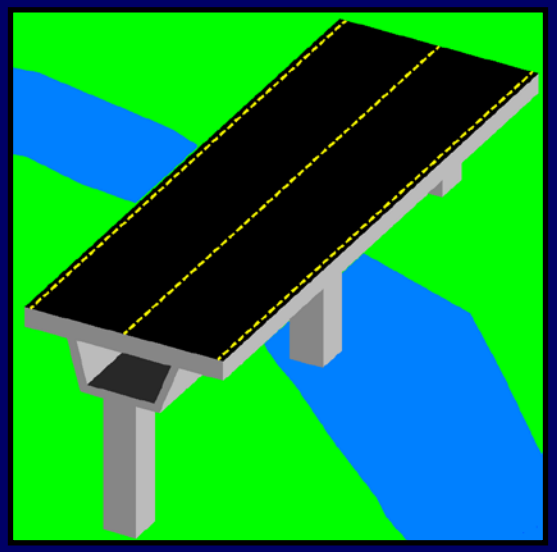
June 2017

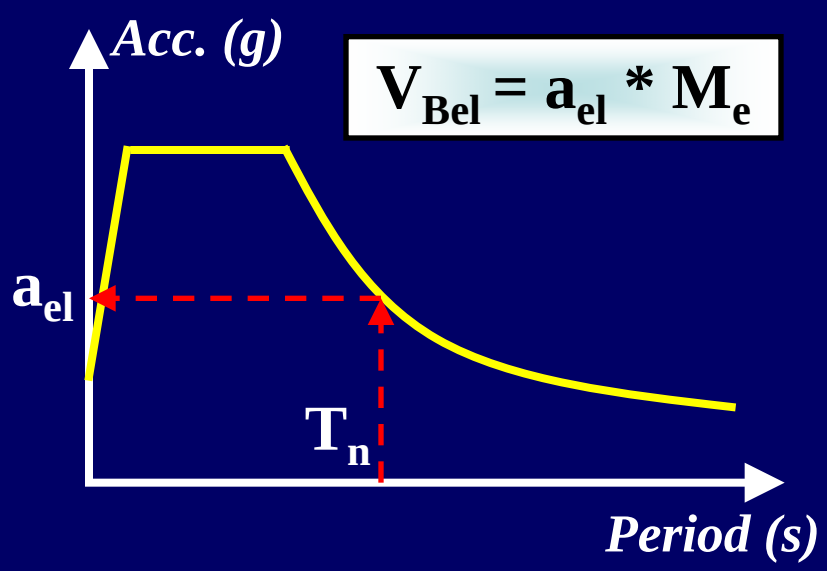
Webinar Schedule

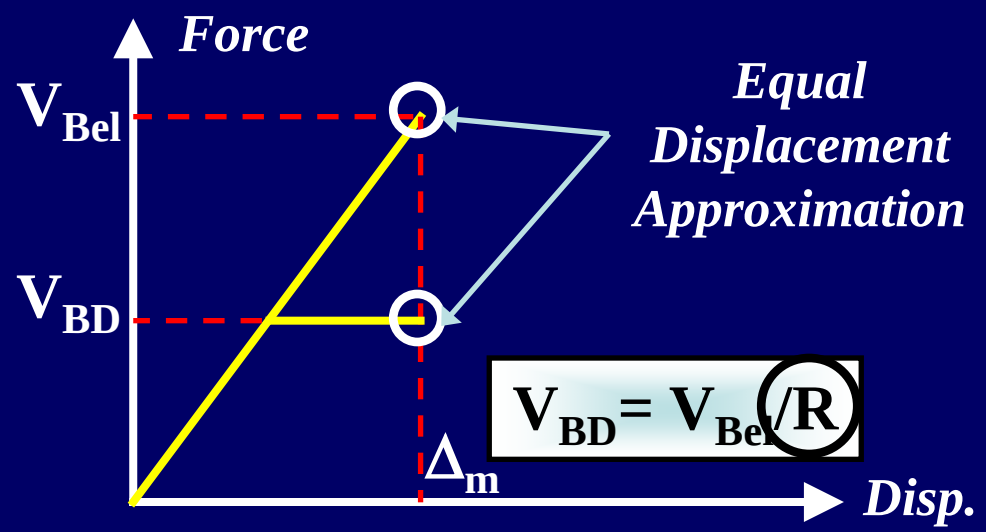
- Introduction and Motivation
- Seismic Demands for DDBD
- Fundamentals of DDBD for SDOF systems.
- Multi-span bridges

Traditional Force-Based Design

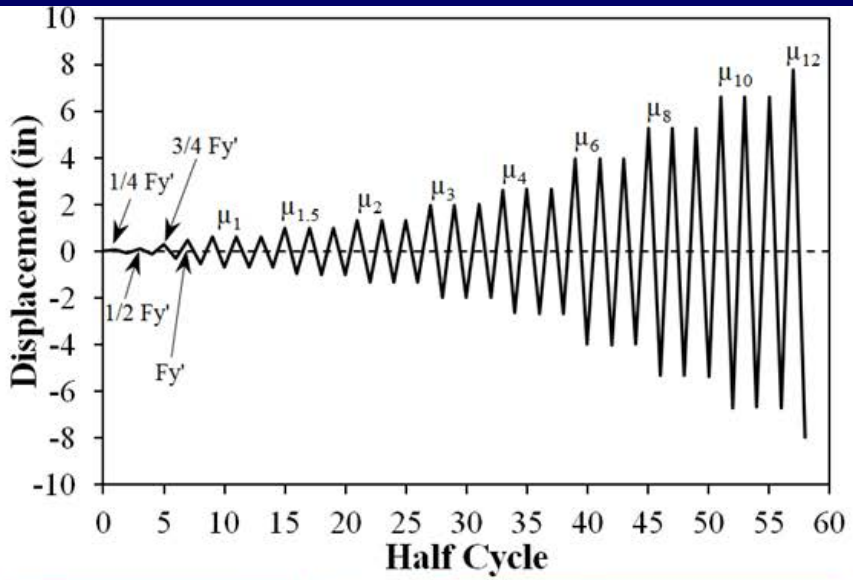


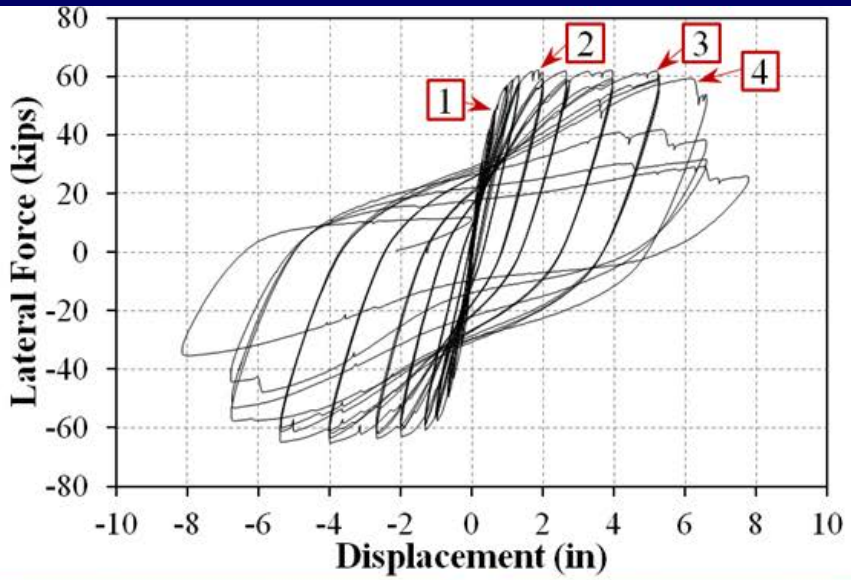
$$T_n = \frac{2\pi}{31.623}\sqrt{\frac{W}{gK}}$$

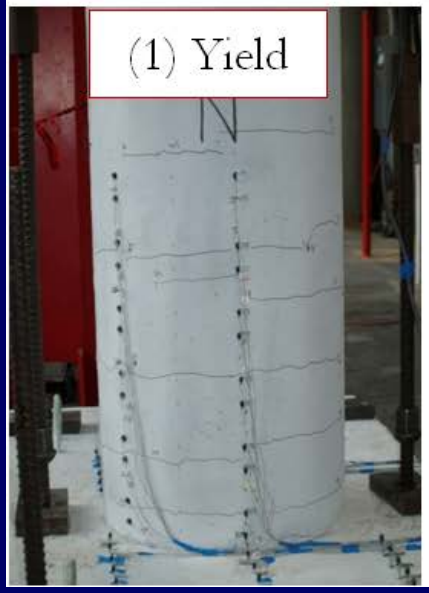


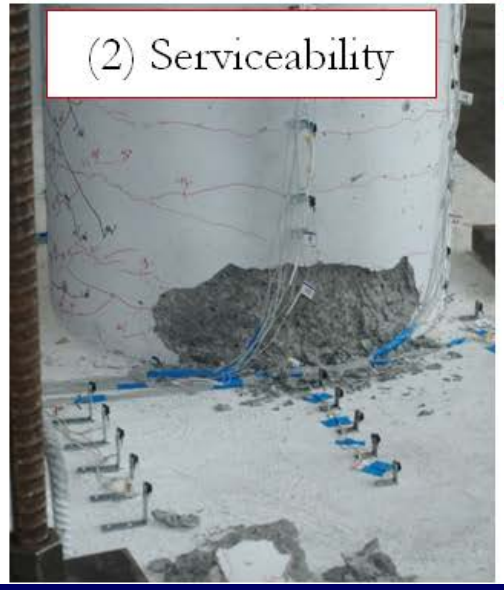


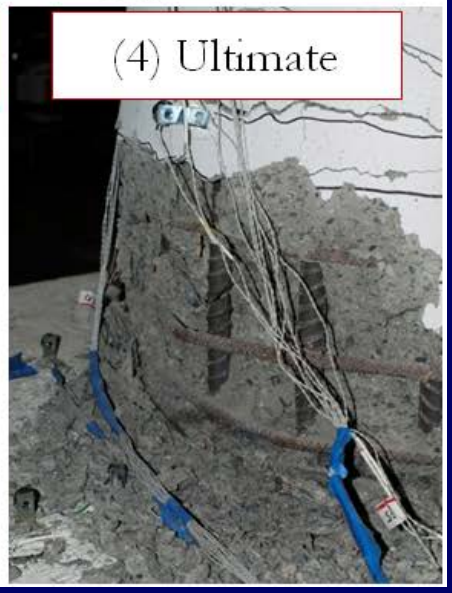
Forces: Poor Indicators of Damage











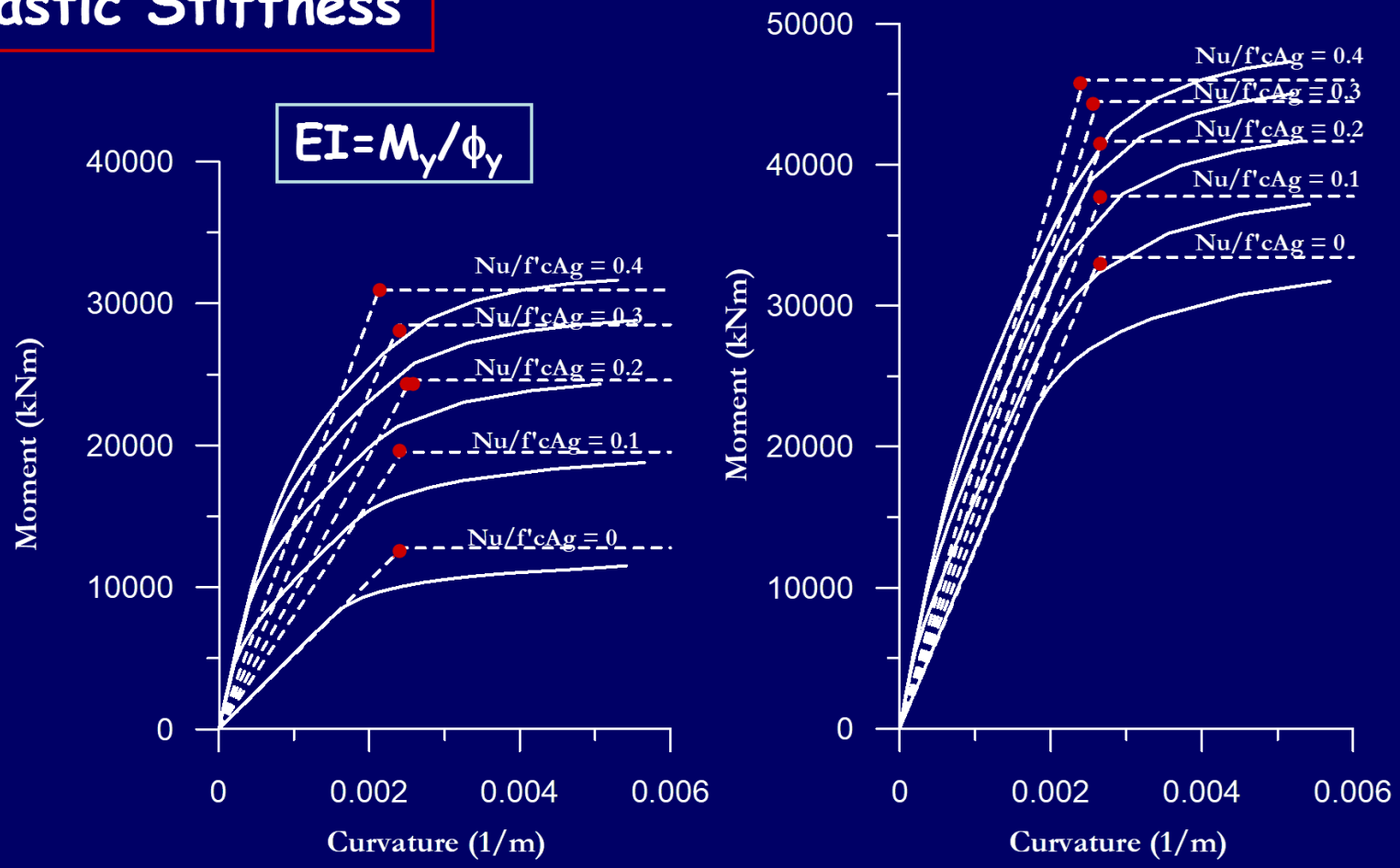
DESIGN TO ELASTIC ACCELERATION SPECTRA (FORCE-BASED DESIGN)

ASSUMPTIONS ARE:

- Elastic force levels (dependent on initial stiffness) are of prime importance
- Elastic stiffness is known at the start of design
- Elastic forces can be reduced by ductility factors, dependent only on material and structural type
- Maximum transient response is the issue. Residual displacement is irrelevant
- Displacements are well estimated by elastic response values
- Safety is increased as strength is increased

Elastic Stiffness

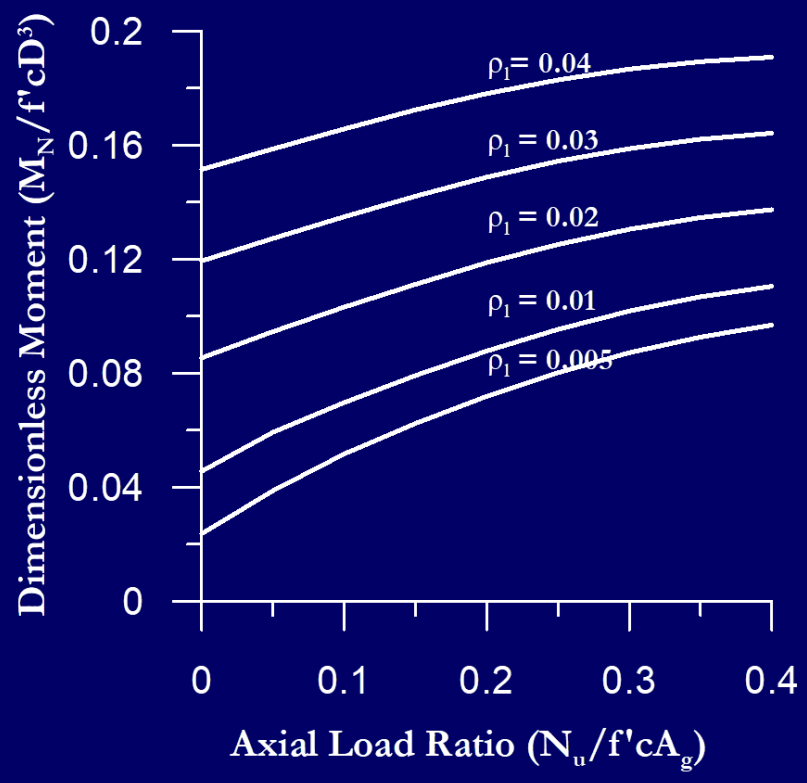
$EI = M_y/\phi_y$



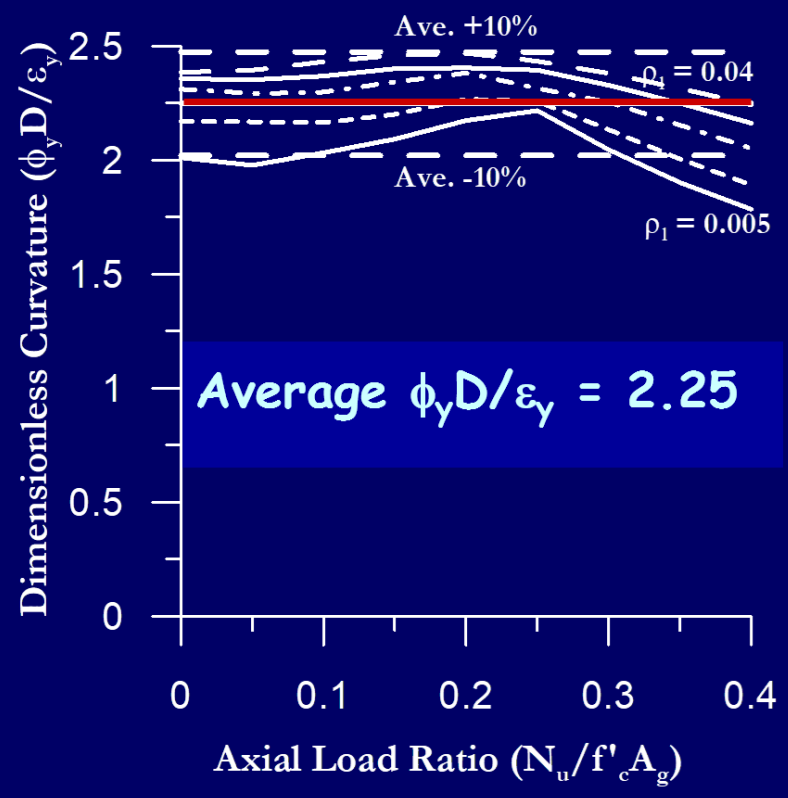
(a) Reinforcement Ratio = 1%

(b) Reinforcement Ratio = 3%

SELECTED MOMENT-CURVATURE CURVES FOR CIRCULAR COLUMNS ($D=2m, f'_c = 35MPa, f_y = 450MPa$)



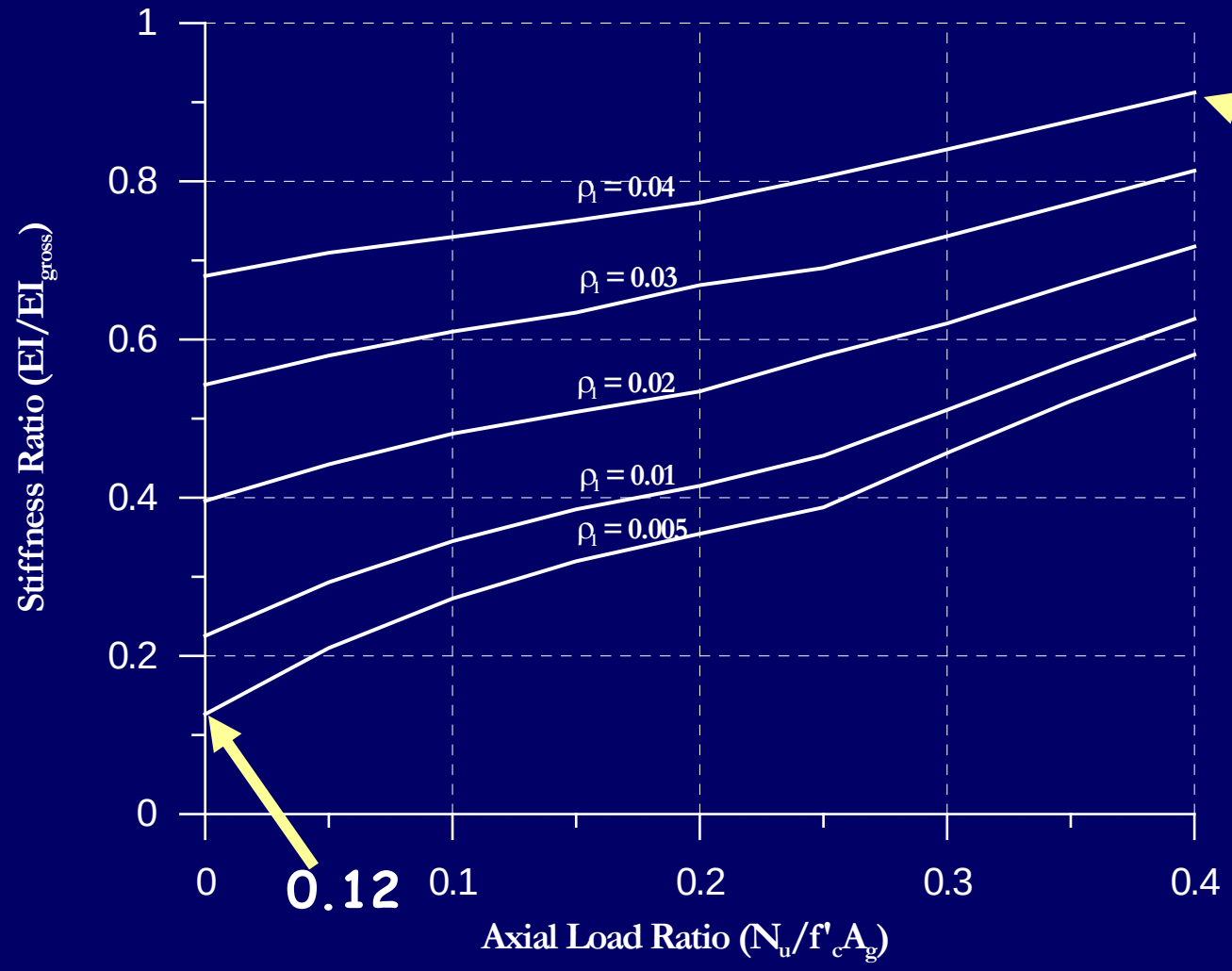
(a) Nominal Moment



(b) Yield Curvature

DIMENSIONLESS NOMINAL MOMENT AND YIELD CURVATURE FOR CIRCULAR COLUMNS

STRENGTH VARIES; YIELD CURVATURE IS CONSTANT



$EI_{eff} = M_N/\phi_y$

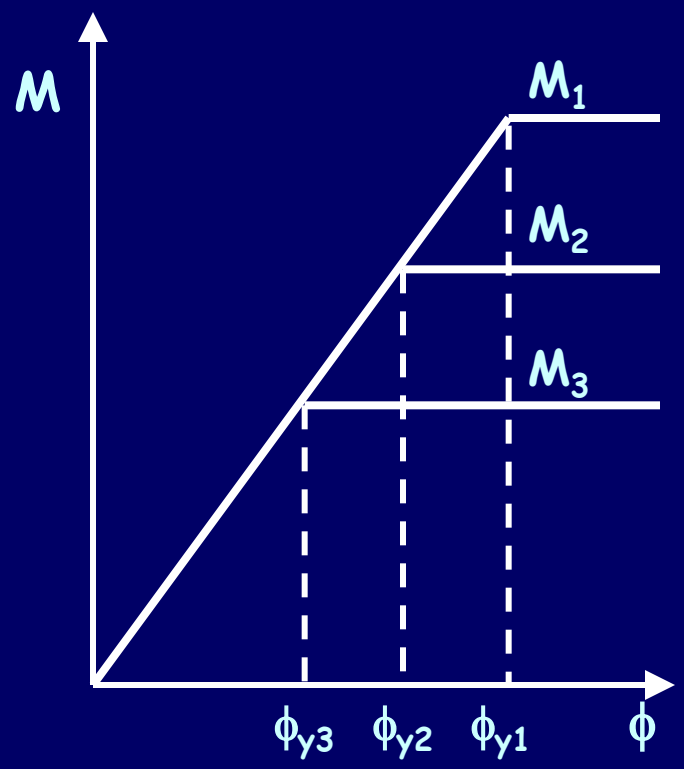
EI_{eff}/EI_{gross}

$= M_N/\phi_y EI_{gross}$

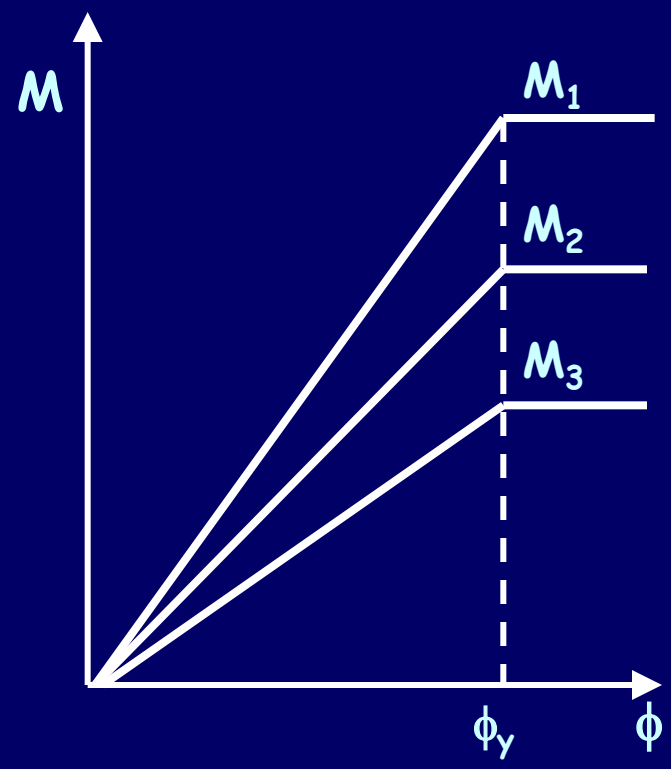
EFFECTIVE STIFFNESS RATIO FOR CIRCULAR COLUMNS

INTERDEPENDENCY OF STRENGTH AND STIFFNESS

Stiffness EI = M/ϕ



(a) Design assumption
(constant stiffness)



(b) Realistic assumption
(constant yield curvature

INFLUENCE OF STRENGTH ON MOMENT-CURVATURE RESPONSE

FORCE-BASED DESIGN – ASSUMPTIONS OF SYSTEM DUCTILITY

- In current force-based design it is assumed that structural systems have a unique ductility capacity, and hence a unique force-reduction factor

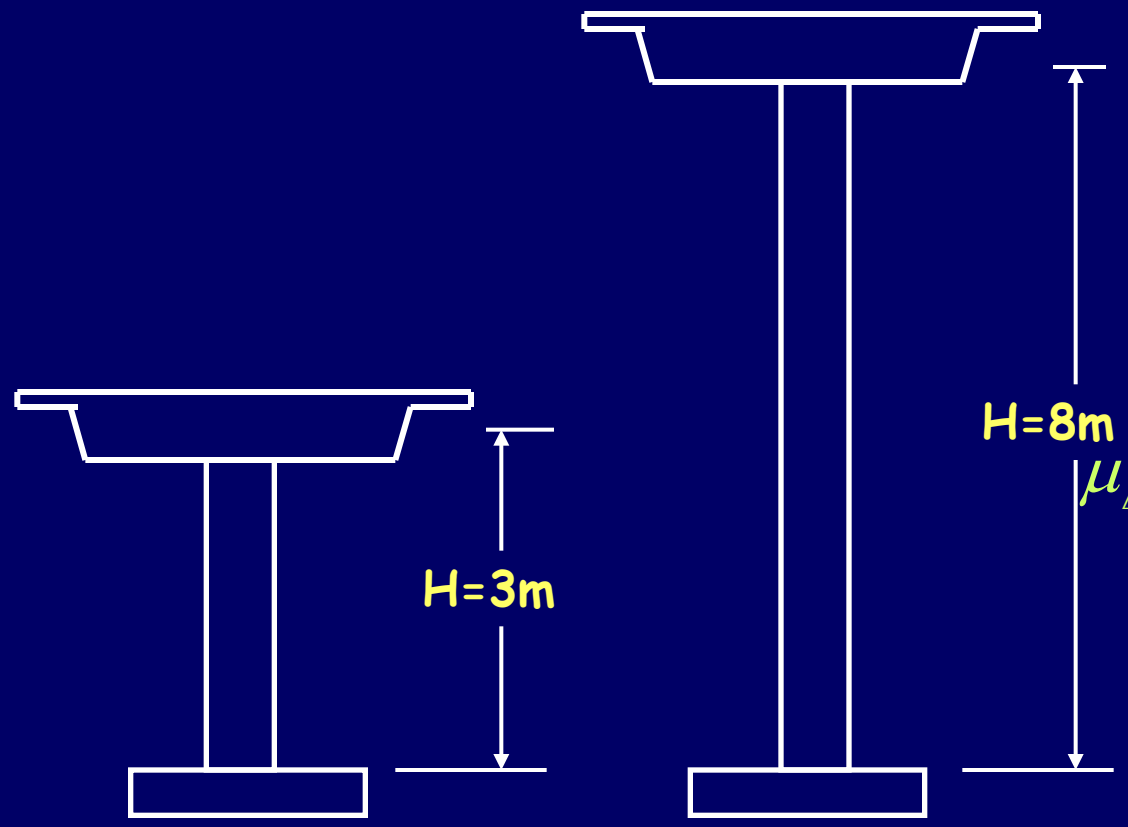
e.g.

Concrete Frame Building: $R_\mu = 6$ (depends on country)

Concrete Wall Building: $R_\mu = 4$ (::)

Concrete Bridge: $R_\mu = 3$ (::)

CONSIDER BRIDGE COLUMNS OF DIFFERENT HEIGHTS



$$\Delta_y = \phi_y H^2 / 3$$

$$\Delta_p = \phi_p L_p H$$

$$\mu_\Delta = \frac{\Delta_y + \Delta_p}{\Delta_y} = 1 + 3\frac{\phi_p L_p}{\phi_y H}$$

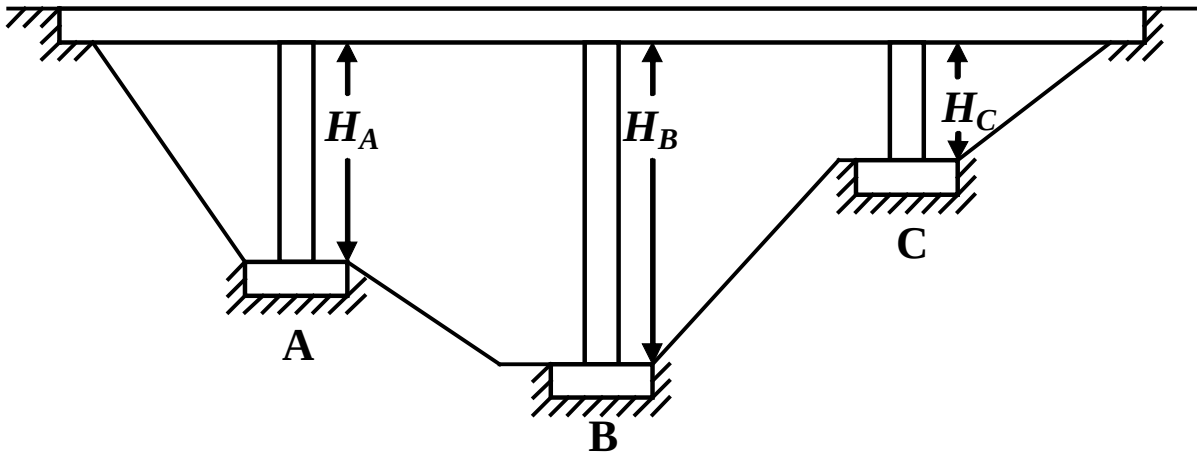
$$L_P = 0.08H + 0.022 d_b f_y$$

(a) Squat Column, μ_Δ=9.4 (b) Slender Column, μ_Δ=5.1

(P/f'cAg=0.1, Rebar = 2% long., 0.6% transverse

$T = 2\pi\sqrt{m / K_{long}}$

Bridge Under Longitudinal Response



Stiffness: $$K_{long} = K_A + K_B + K_C = \sum_{A,B,C} \frac{12EI}{H^3}$$

Period: $$T = 2\pi\sqrt{m / K_{long}}$$

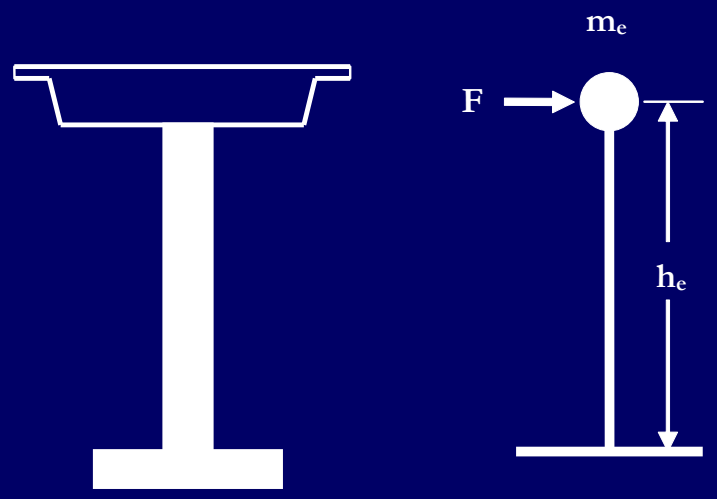
Pier Strength: $$F_i = F\frac{K_i}{K_{long}}$$

What value to use for EI? What ductility?

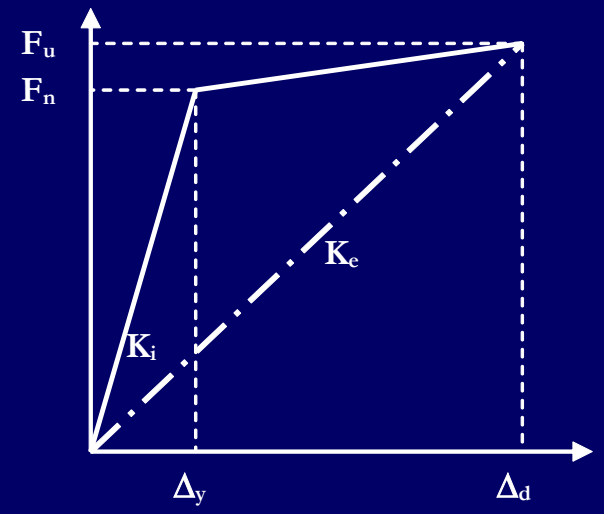
Direct Displacement-Based Design: What's Different?

- Design for a target damage level.
- Use displacement spectra to define hazard.
- Consider energy dissipation via equivalent viscous damping.
- Start with target displacement – end with required strength and stiffness.

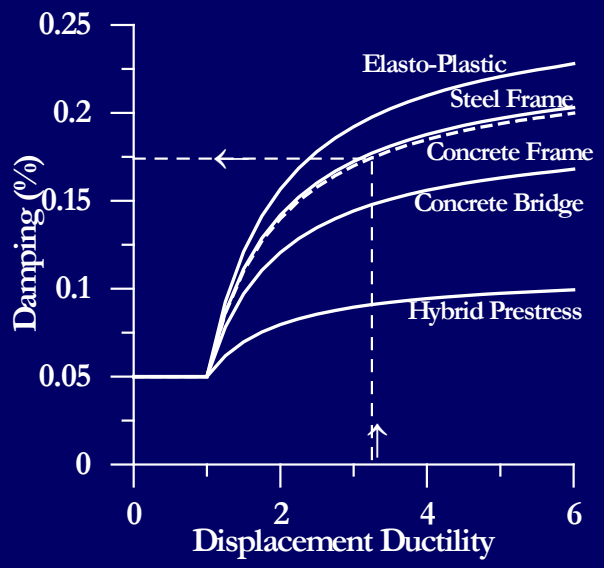
FUNDAMENTALS OF DDBD



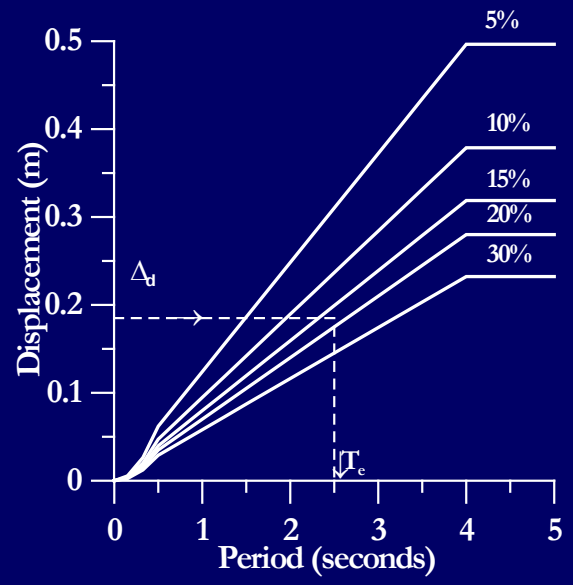
(a) SDOF Simulation



(b) Effective Stiffness K_e



(c) Equivalent damping vs. ductility



(d) Design Displacement Spectra

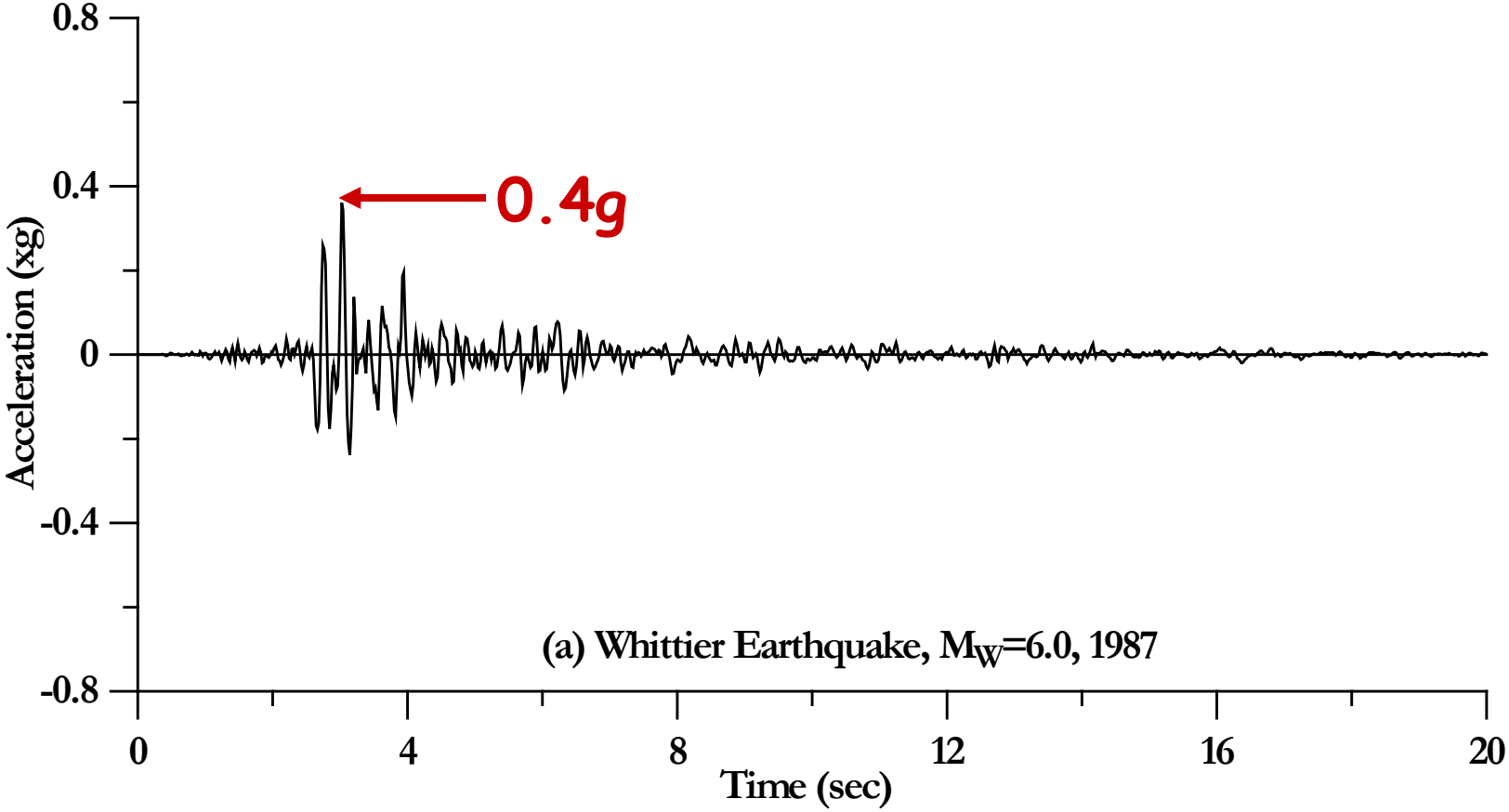
Session 2

Characterization of Seismicity for Displacement-Based Seismic Design

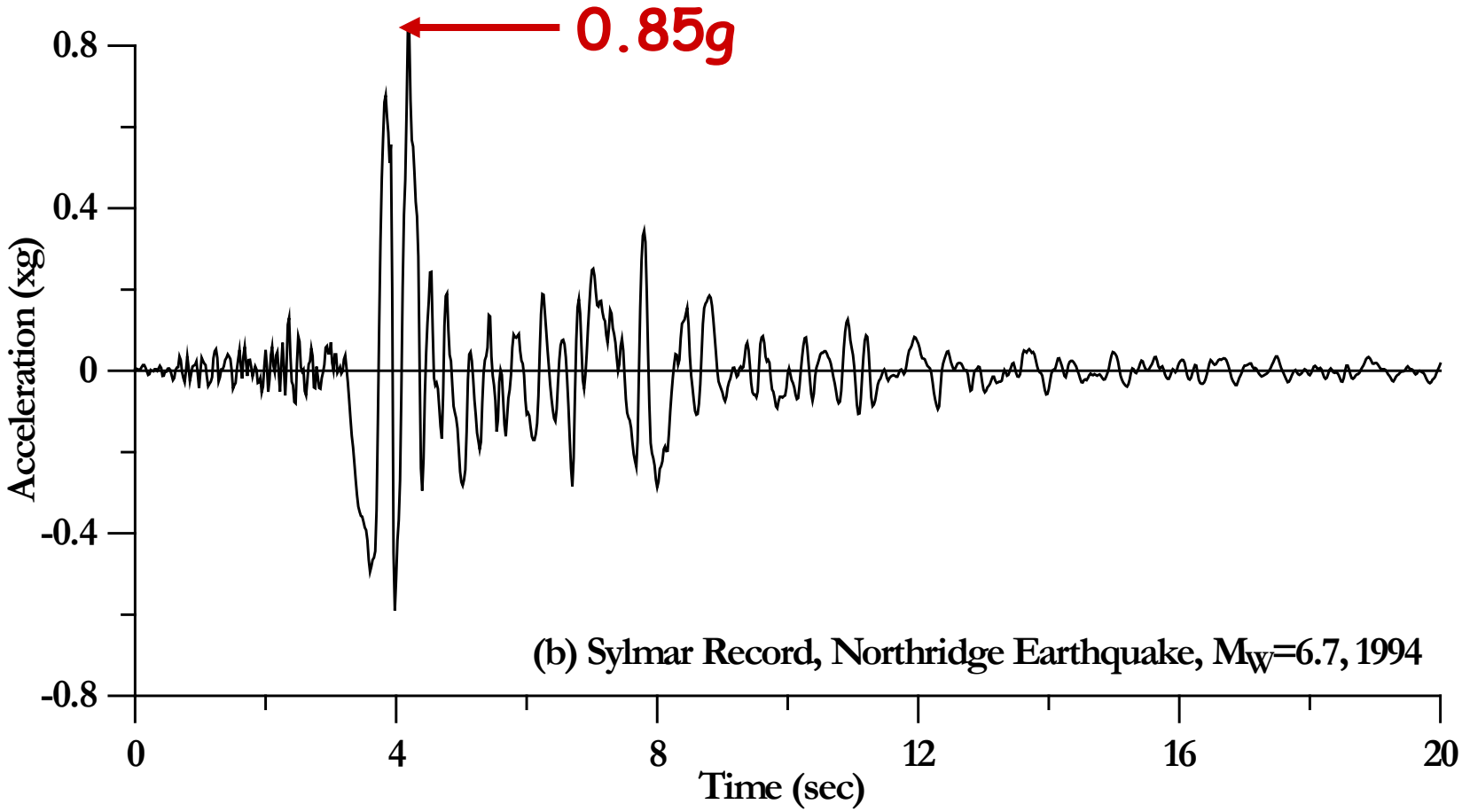
Seismicity Outline

- Time histories
- Response Spectra
- Seismic Input for DDBD

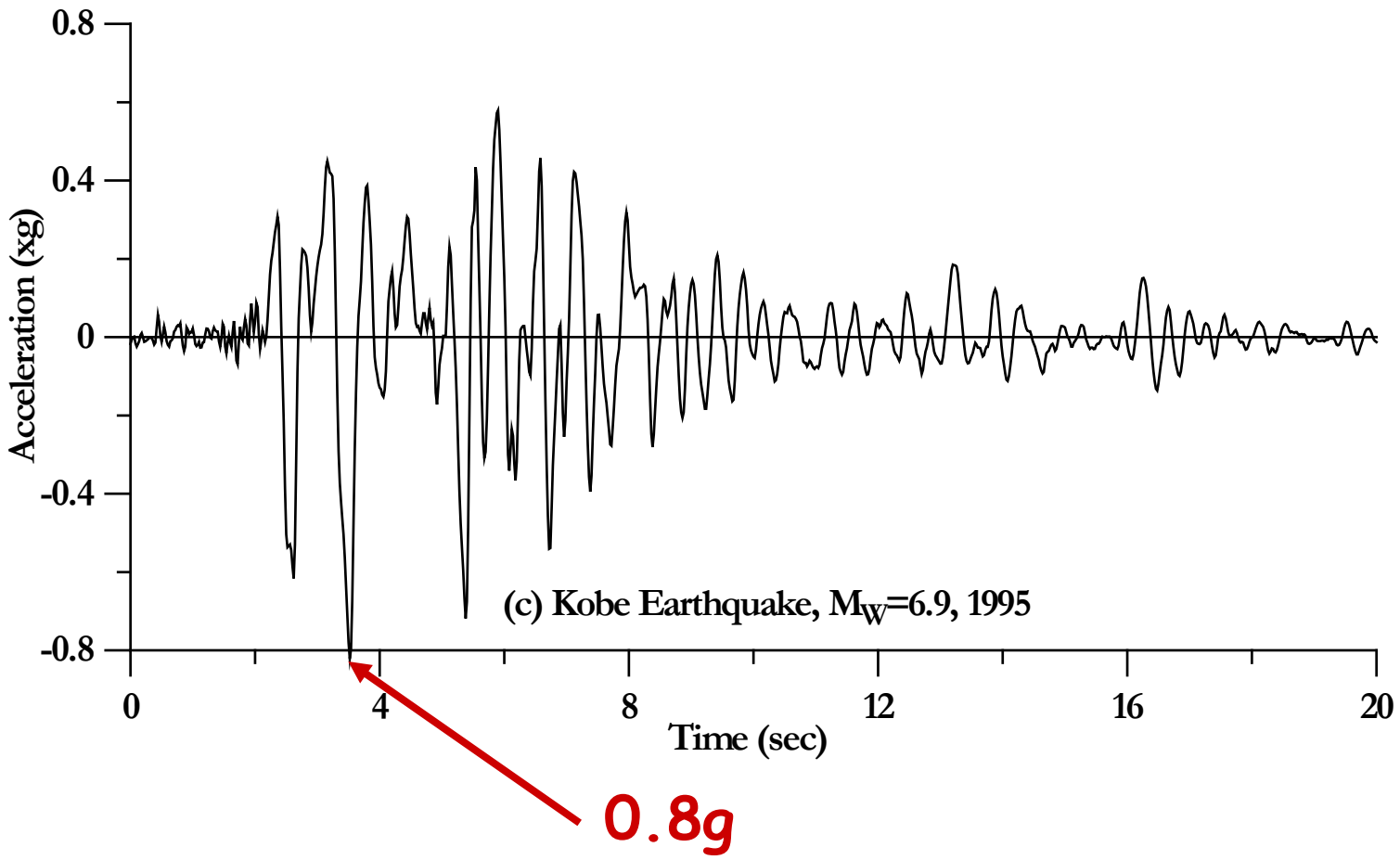
WHITTIER NARROWS 1987, Mw = 6.0 (15 km)
ACCELEROGRAM



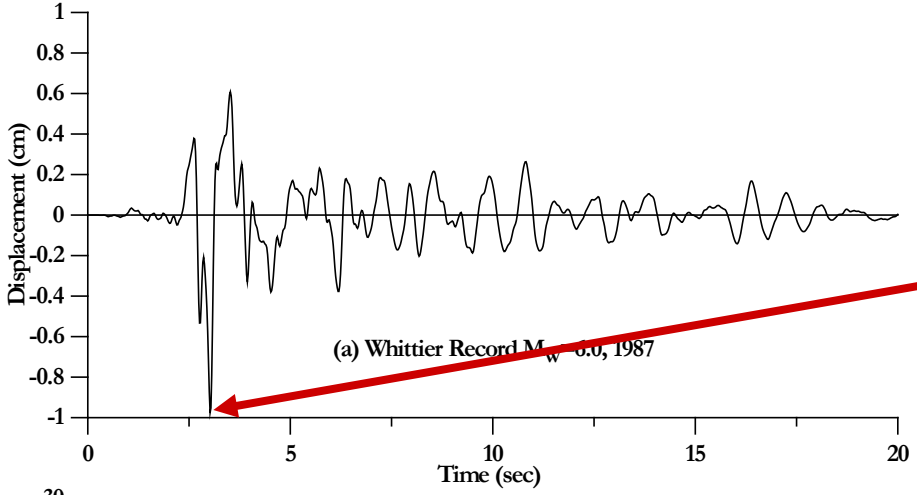
NOTRTHRIDGE, 1994, Mw=6.7 (6km) ACCELEROGRAM



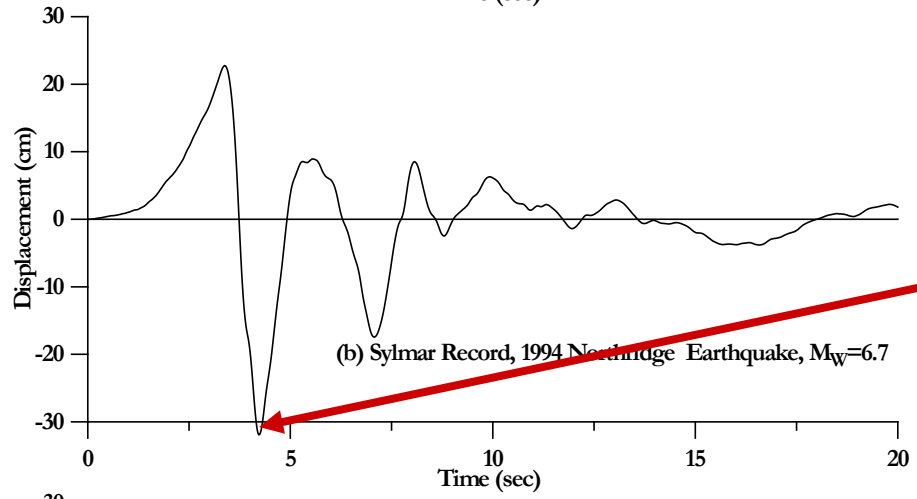
KOBE, 1995, Mw=6.9 (1 km) ACCELEROGRAM



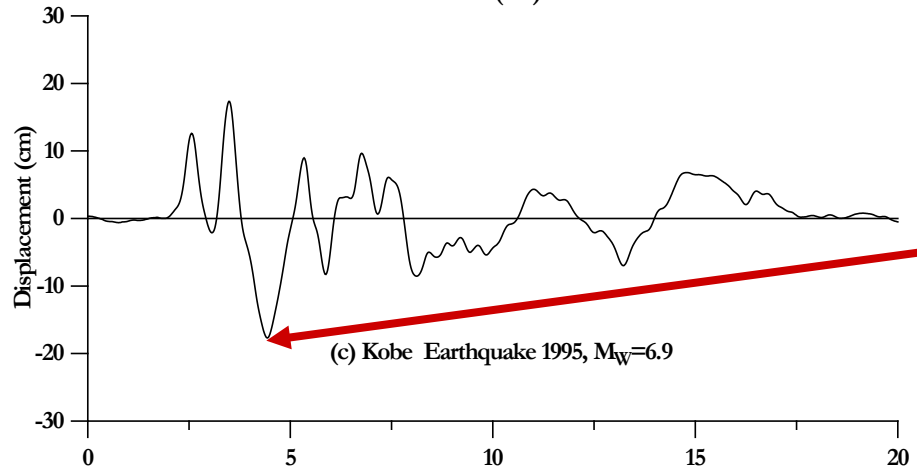
GROUND DISPLACEMENT



Whittier, 1.0cm



Northridge, 30cm

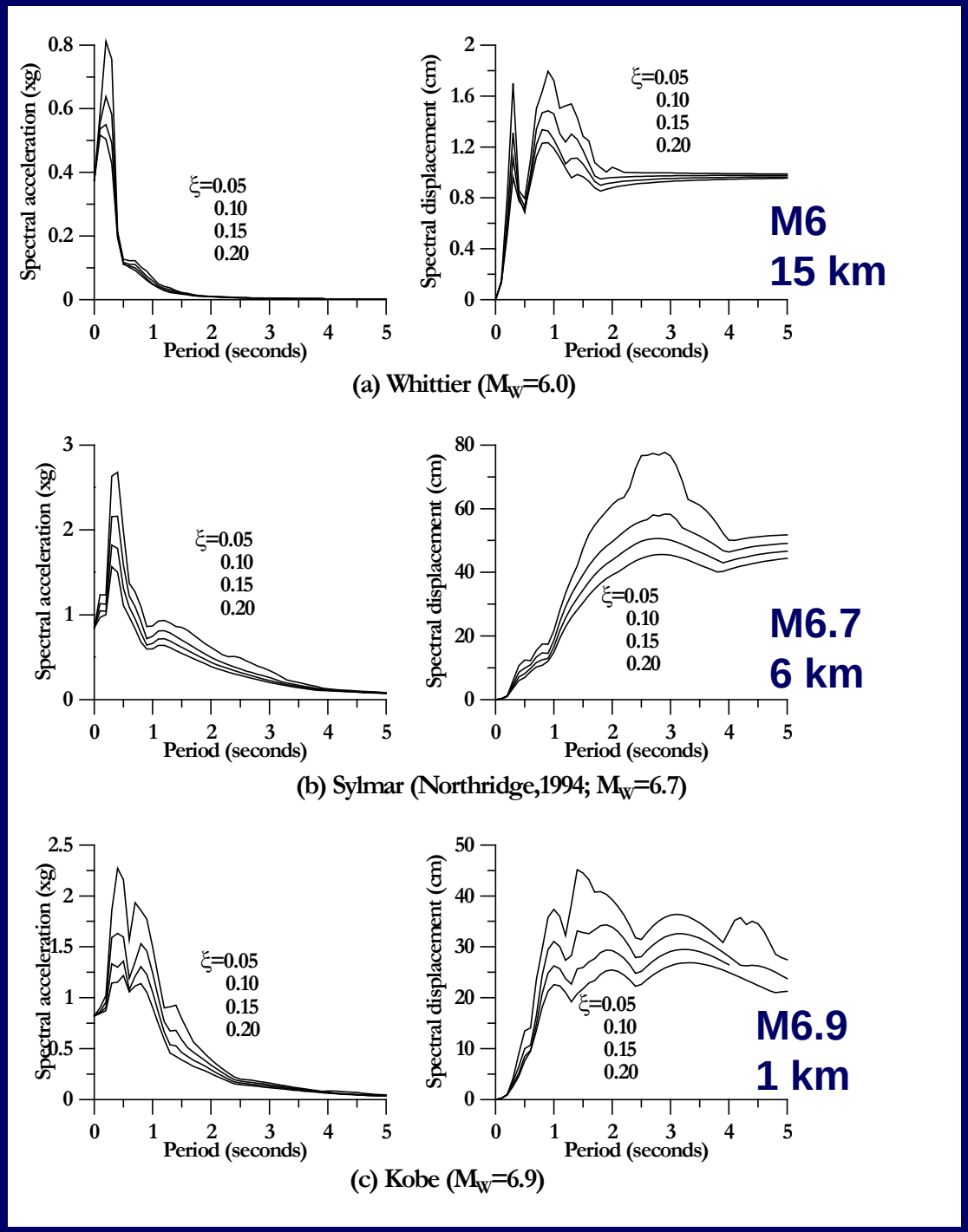


Kobe, 20cm

Time History Observations

- Acceleration time histories give an incomplete picture of an EQ
- Frequency content may be influenced by distance to source
- Displacement time histories expose large differences between earthquakes of comparatively similar PGAs

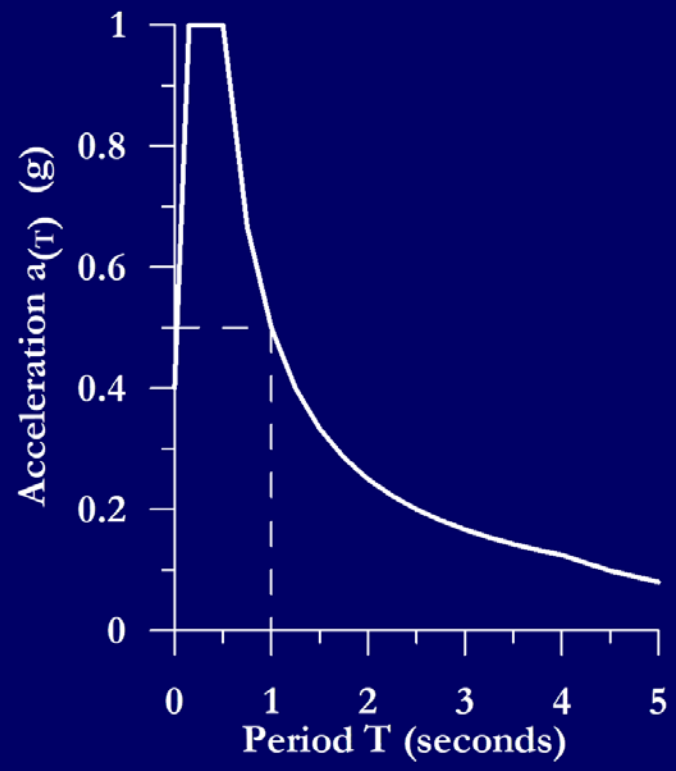
ARS and DRS of Selected Records



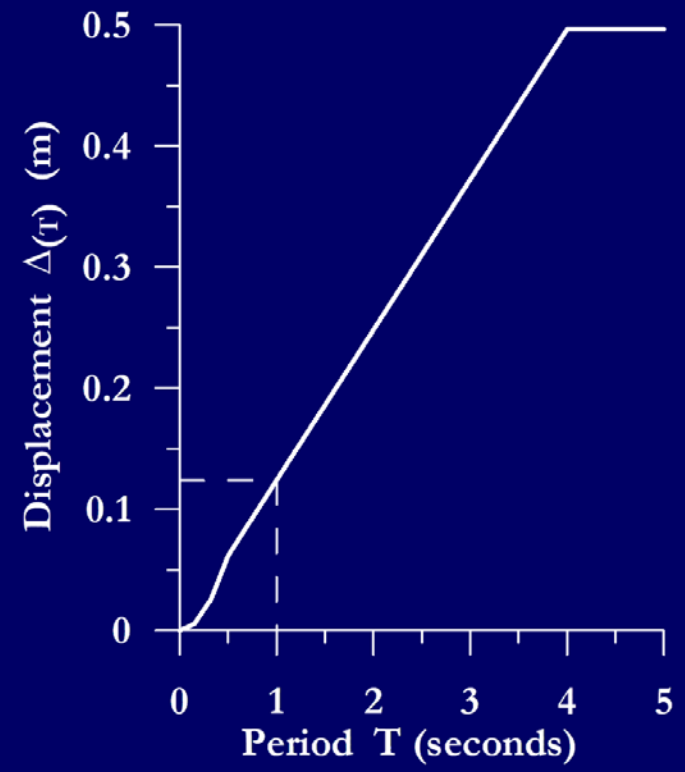
Response Spectra Observations

- ARS do not give the complete picture of damage potential of an EQ
- EQs with large PGAs do not necessarily indicate large potential for damage.
- Distance to source plays an important role in defining damage potential of an EQ

Seismic Input for DDBD



(a) Acceleration Spectrum for 5% damping



(b Displacement Spectrum for 5% damping

Force-based design

DDBD

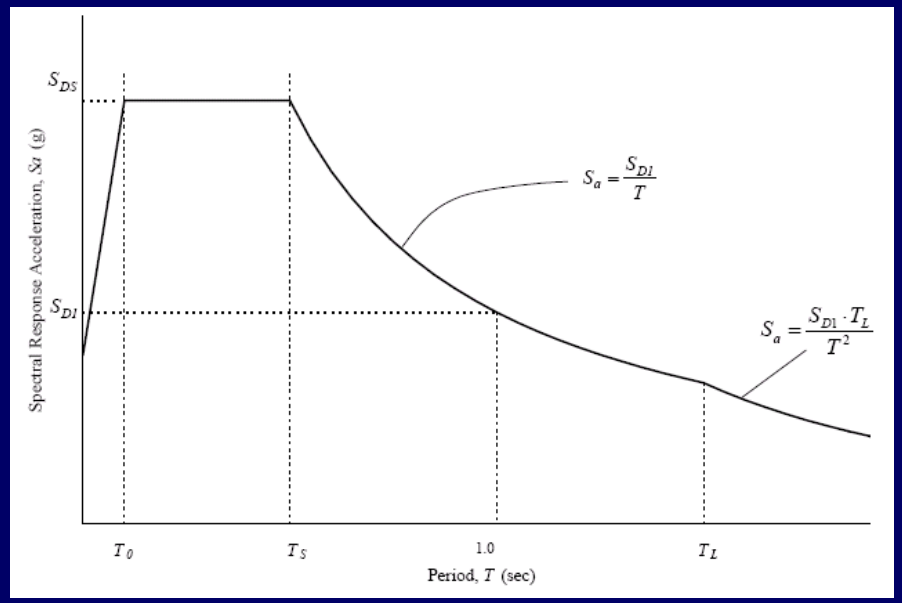
DRS Options

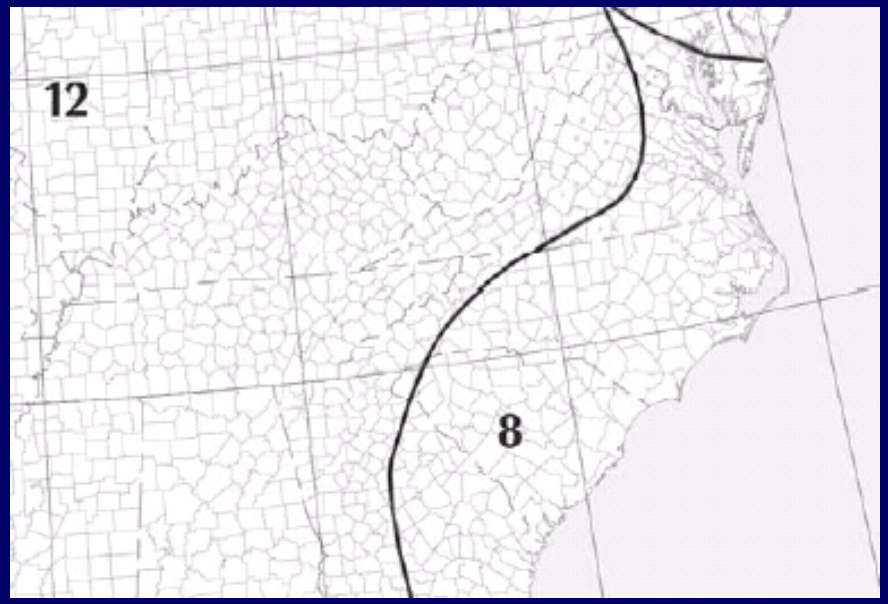
- Approximate from code ARS
- Direct calculation from code specified parameters (i.e. EuroCode)
- Ground motion prediction equations (magnitude-distance relationships) for DRS, or converted from ARS.
- Site-specific evaluation

Option One: DRS from ARS

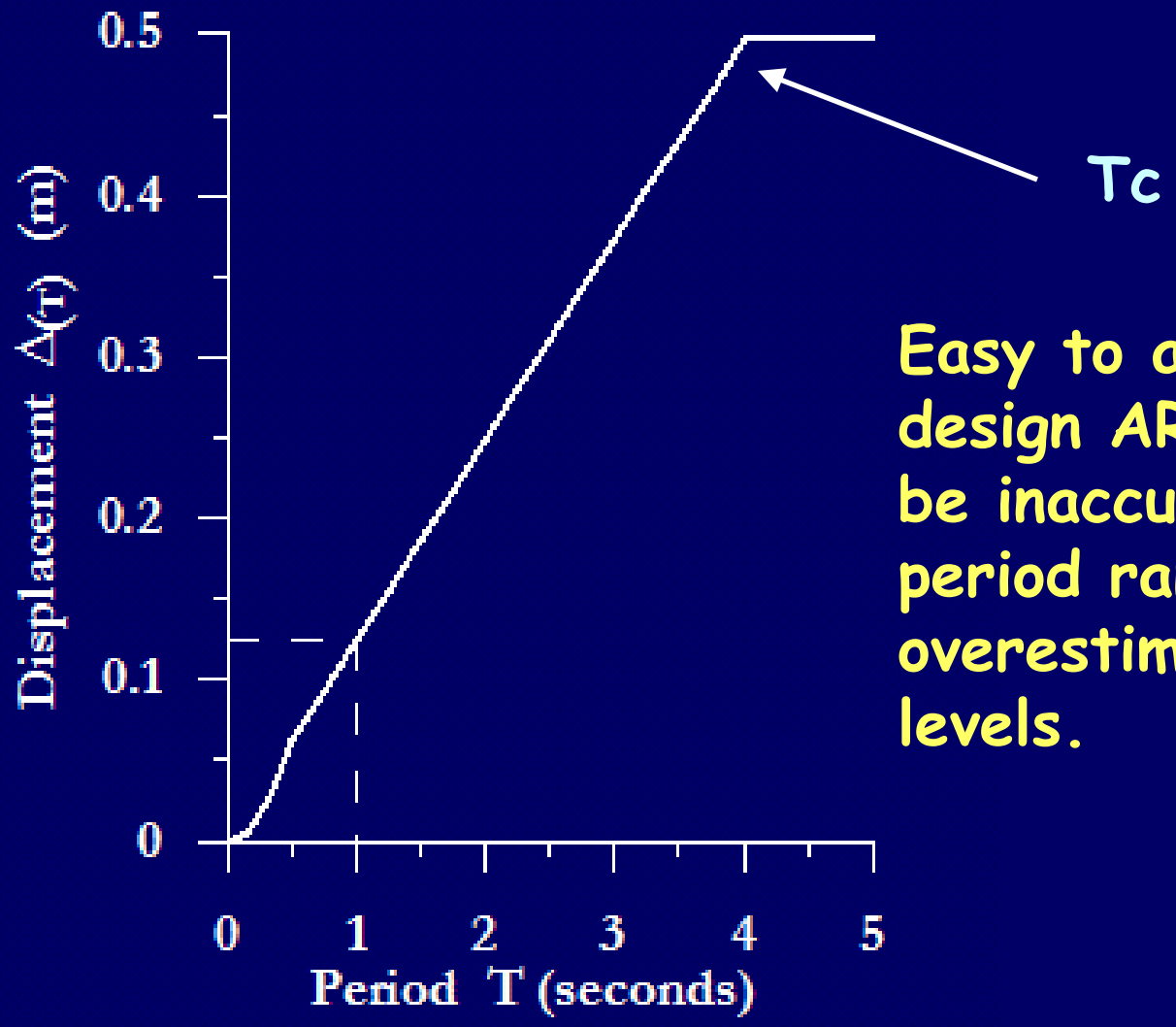
- Can be approximately generated from design acceleration spectra (5% damping) using acceleration-displacement relationships:

$$\Delta_{(T,5)} = (T^2/4\pi^2).g.a_{(T,5)}$$



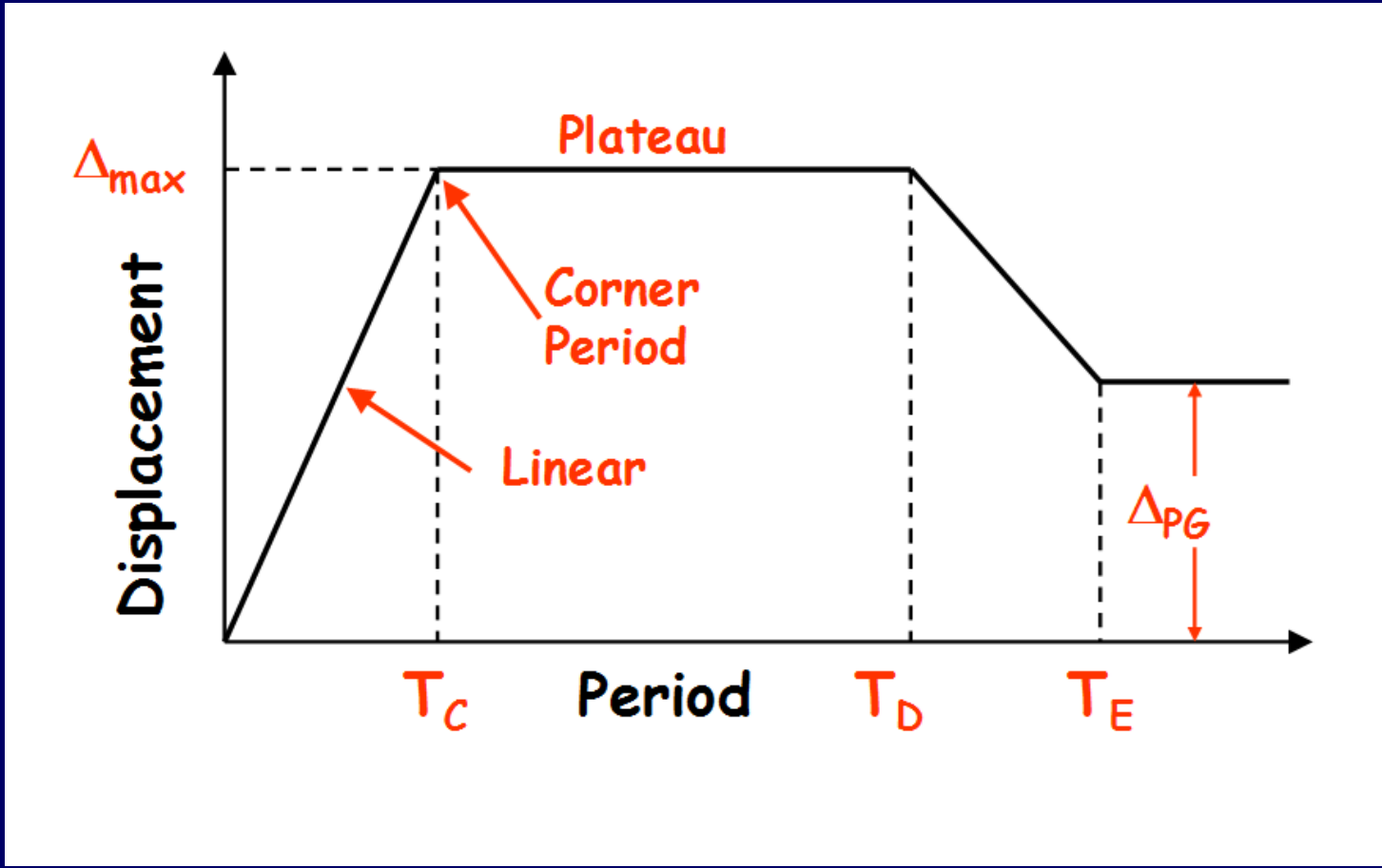


Derived ASCE 7 Displacement Spectra



Easy to apply, however, design ARS may be inaccurate in the long period range, likely overestimating response levels.

Option Two: Code DRS



Ideal option, however, only EuroCode defines DRS directly

Option Three: GMPEs

- Numerous GMPEs for ARS that could be converted to DRS by dividing by ω^2 as in option one.
- Preferable to use GMPE that directly defines DRS, i.e. Faccioli, 2004 and 2010.

DESIGN DISPLACEMENT SPECTRA (4)

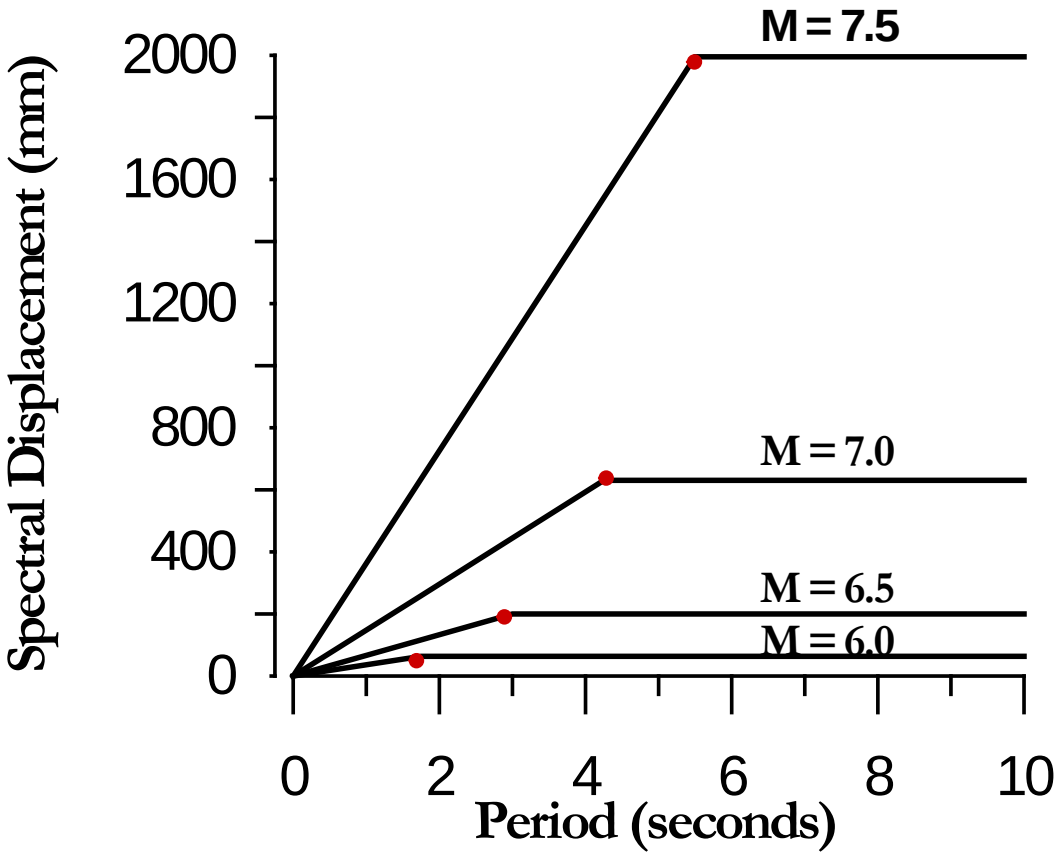
- Based on Faccioli's observations, the corner period T_c appears to increase almost linearly with moment magnitude. For earthquakes with $M_W > 5.7$, the following expression seems conservative:

$$T_c = 1.0 + 2.5(M_w - 5.7) \text{ seconds}$$

- Peak displacement at the corner period can be estimated from the following expression (firm ground):

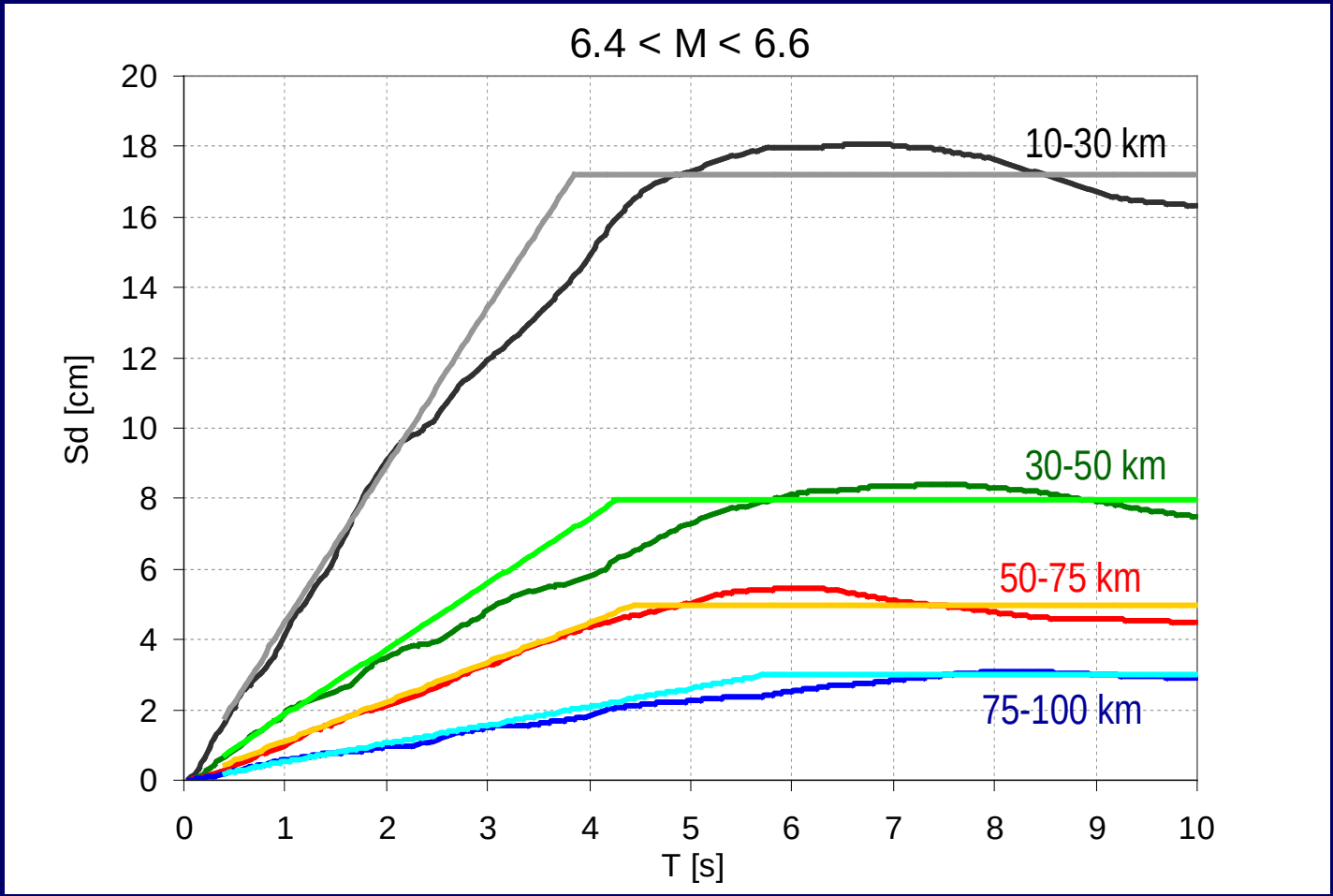
$$\delta_{\max} = \frac{10^{(M_W - 3.2)}}{r} \text{ mm}$$

r = nearest distance to fault plane (km)



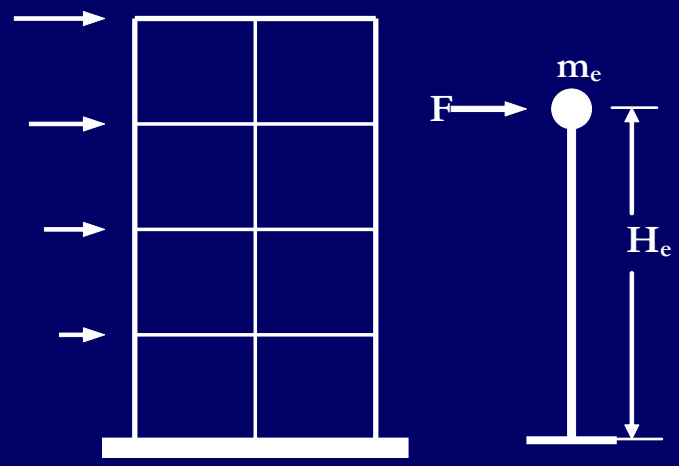
5% Damped Spectra Resulting from the Equations, at r = 10km

Comparison of 2004 Faccioli Model with actual Data

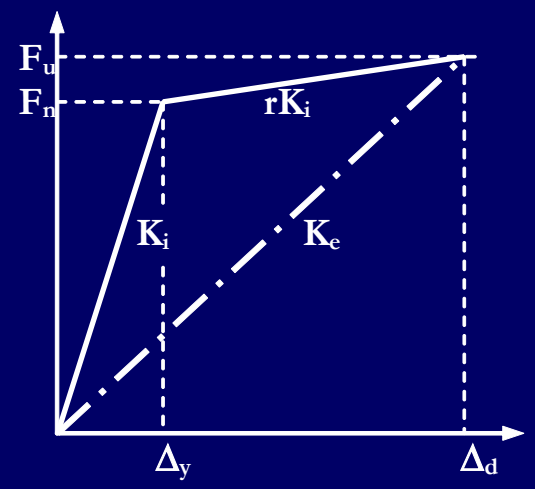


SESSION 3
Fundamentals of Displacement-Based Seismic Design

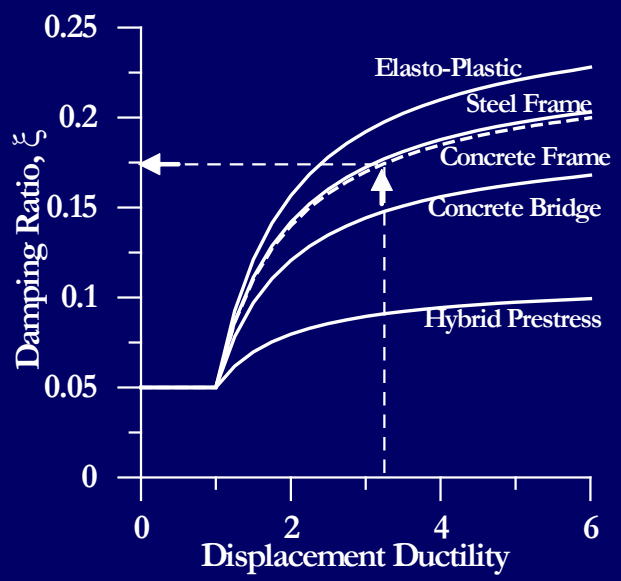
FUNDAMENTALS OF DDBD



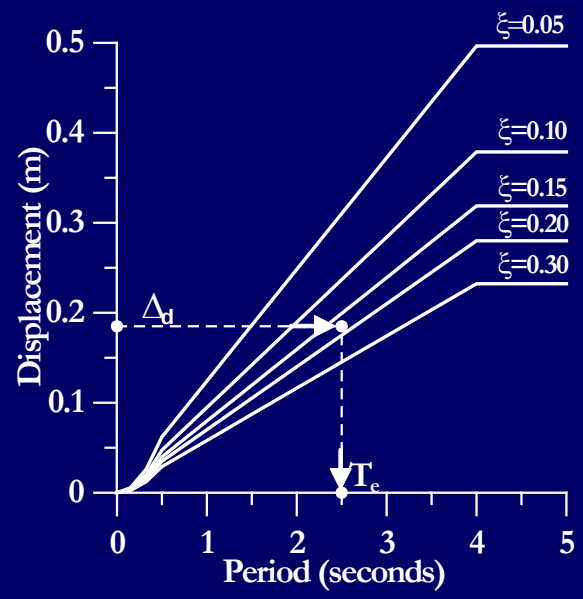
(a) SDOF Simulation



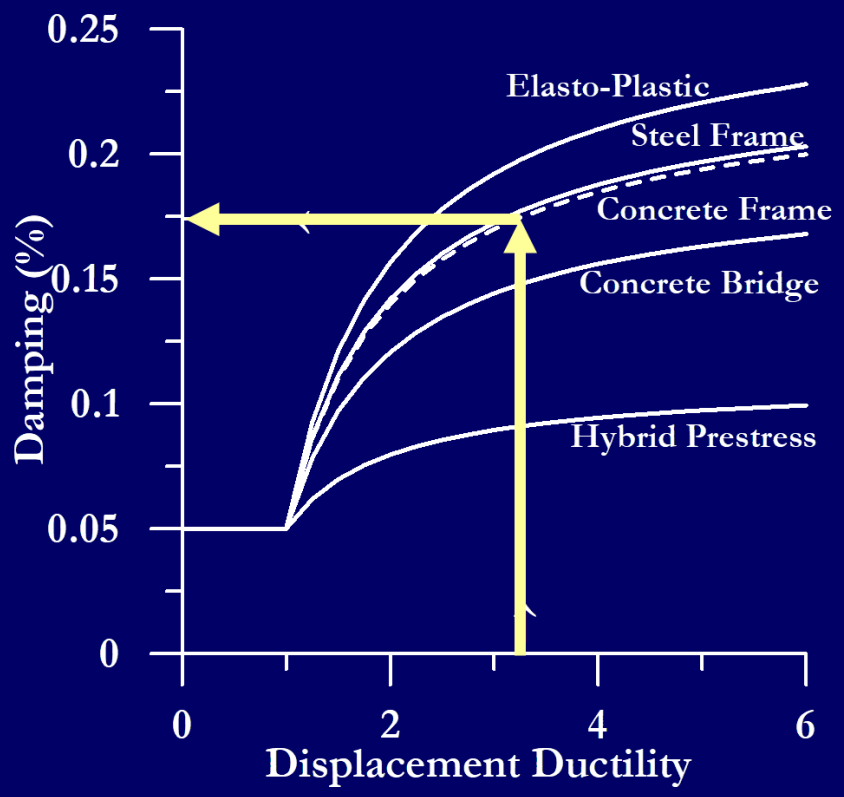
(b) Effective Stiffness K_e



(c) Equivalent damping vs. ductility



(d) Design Displacement Spectra



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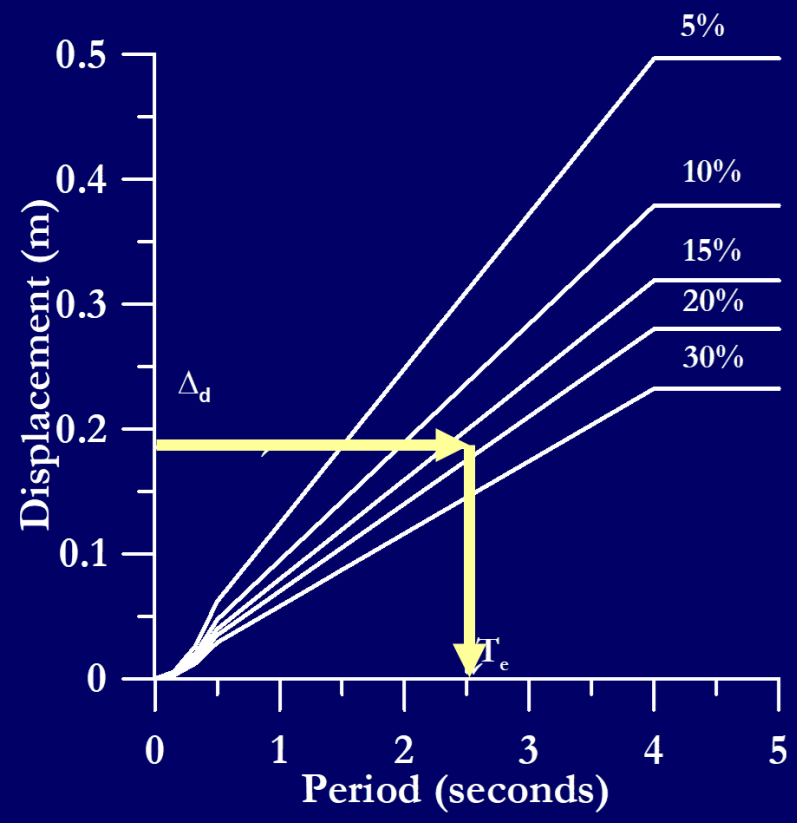
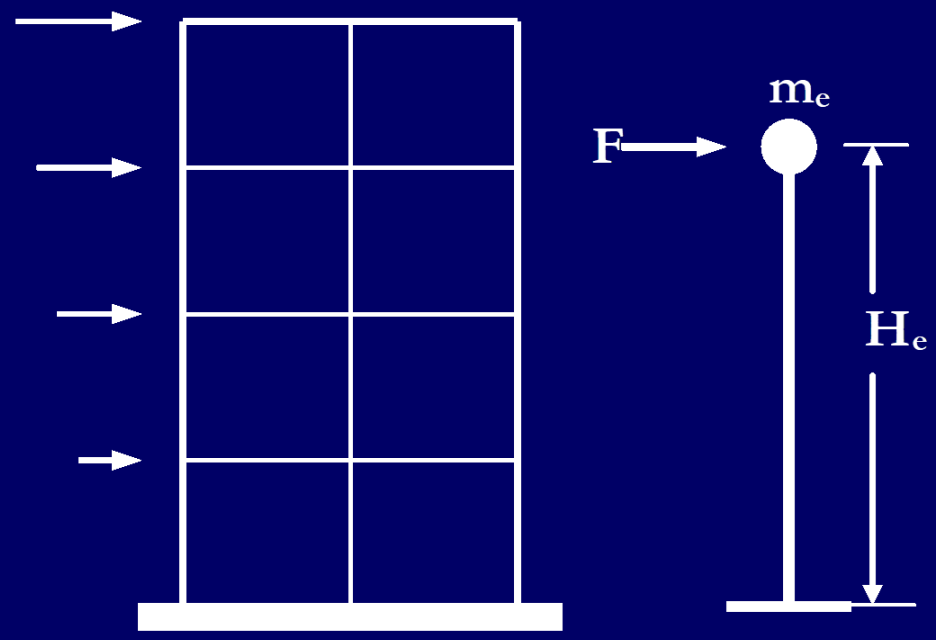
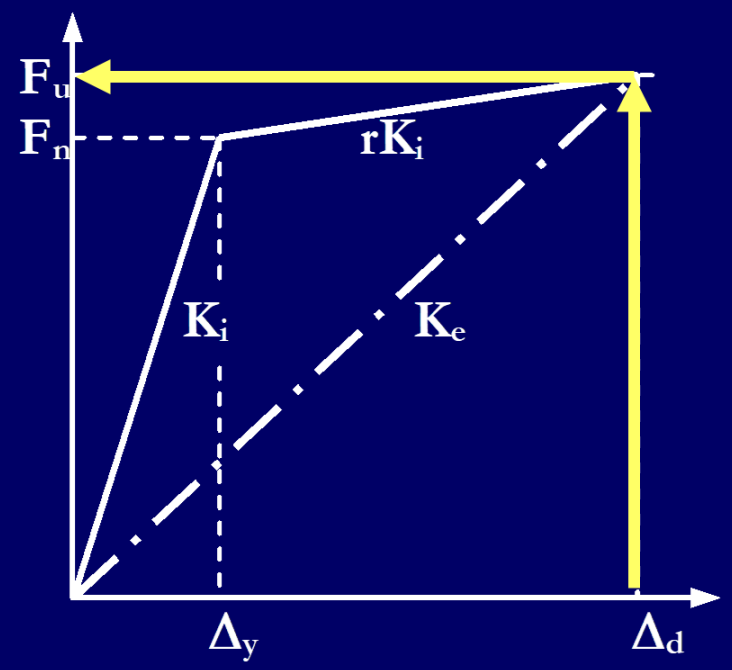


(d) Design Displacement Spectra

Limit State → Displacement; Ductility → Damping

Damping+Displacement → T_e; $K=4\pi^2 m_e/T_e^2$



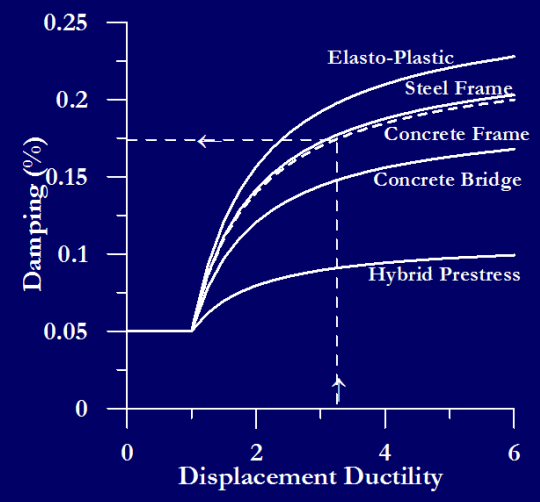


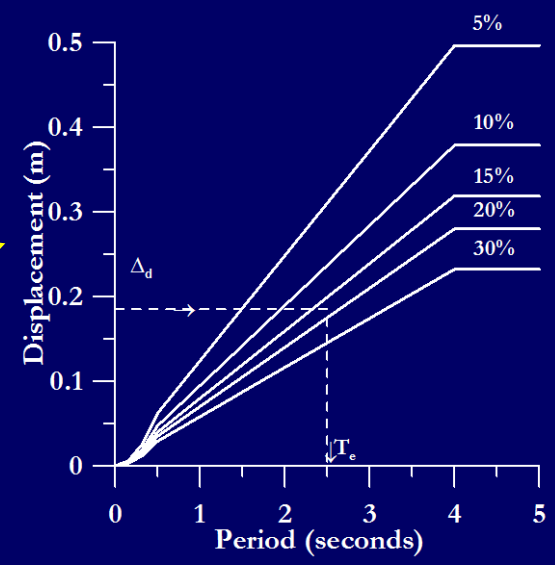
Limit State ⟶ Displacement; Ductility ⟶ Damping

Damping+Displacement ⟶ Te; $K=4\pi^2 me/T_e^2$

$$F_u = K_e \Delta_d$$

- Select target displacement, Δ_d
  - Strain, Drift, or Ductility
- Calculate yield displacement, Δ_y
  - Fundamental member property
- Calculate equivalent viscous damping, ζ
  - Relationships between damping and ductility available and easily obtained
- Calculate effective period, T_{eff}
  - From Response spectra
- Calculate effective stiffness, K_{eff}
  - $K_{eff} = 4\pi^2 m / T_{eff}^2$
- Calculate design base shear force, V_b
  - $V_b = K_{eff}\Delta_d$





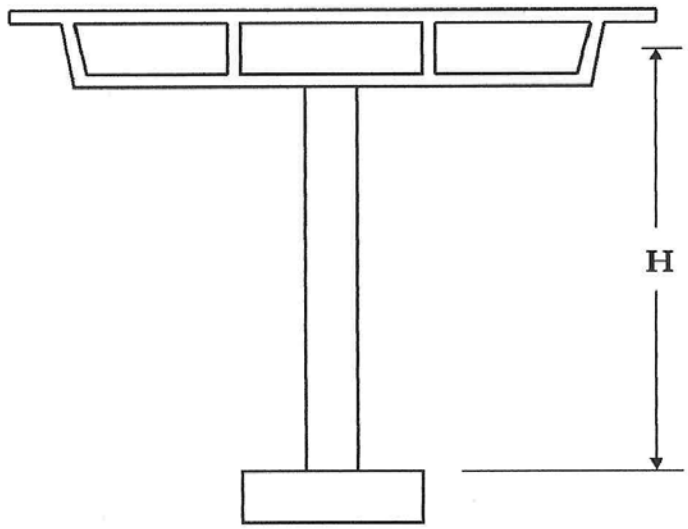
DIRECT DISPLACEMENT-BASED DESIGN

SINGLE-DEGREE-OF-FREEDOM STRUCTURES

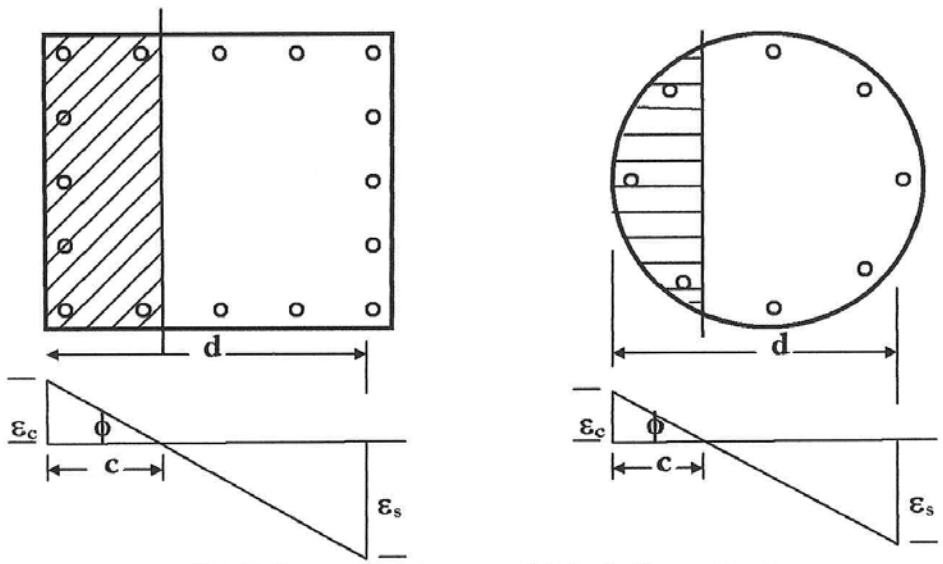
1. DESIGN DISPLACEMENT FOR S.D.O.F STRUCTURES

- Depends on Design Limit State
- Structural displacement limit: Strain related, Ductility related
- Non-structural displacement limit: Drift related
- chose critical of structural and non-structural limit displacements

EXAMPLE OF STRAIN LIMIT STATES



(a) Cantilever Bridge Column



(b) Column Sections and Limit State Strains

Curvature from concrete compression:

$$\phi_{mc} = \varepsilon_{cm}/c$$

Curvature from reinforcement tension:

$$\phi_{ms} = \varepsilon_{sm}/(d-c)$$

Chose lesser of ϕ_{mc} and ϕ_{ms},

Design Displacement is:

$$\Delta_{ds} = \Delta_y + \Delta_p$$

$$= \phi_y H^2/3 + (\phi_m - \phi_y) L_p H$$

L_p = plastic hinge length.

2. DUCTILITY

Damping depends on the design displacement ductility:

$$\mu_\Delta = \Delta_d/\Delta_y$$

NOTE: The yield displacement is independent of strength, and is thus known at the start of the design process (provided section size is known). Hence ductility is known at the start of the design process.

DIMENSIONLESS YIELD CURVATURES AND DRIFTS

- Circular column: $\phi_y = 2.25\varepsilon_y / D$
- Rectangular column: $\phi_y = 2.10\varepsilon_y / h_c$
- Rectangular cantilever walls: $\phi_y = 2.00\varepsilon_y / l_w$
- T-Section Beams: $\phi_y = 1.70\varepsilon_y / h_b$

Concrete Frames: $\theta_y = 0.5\varepsilon_y \dfrac{l_b}{h_b}$

Steel Frames: $\theta_y = 0.65\varepsilon_y \dfrac{l_b}{h_b}$

For S.D.O.F. structure:

Yield displacement = $\phi_y.H^2/3$; (or $\theta_y H_e$)

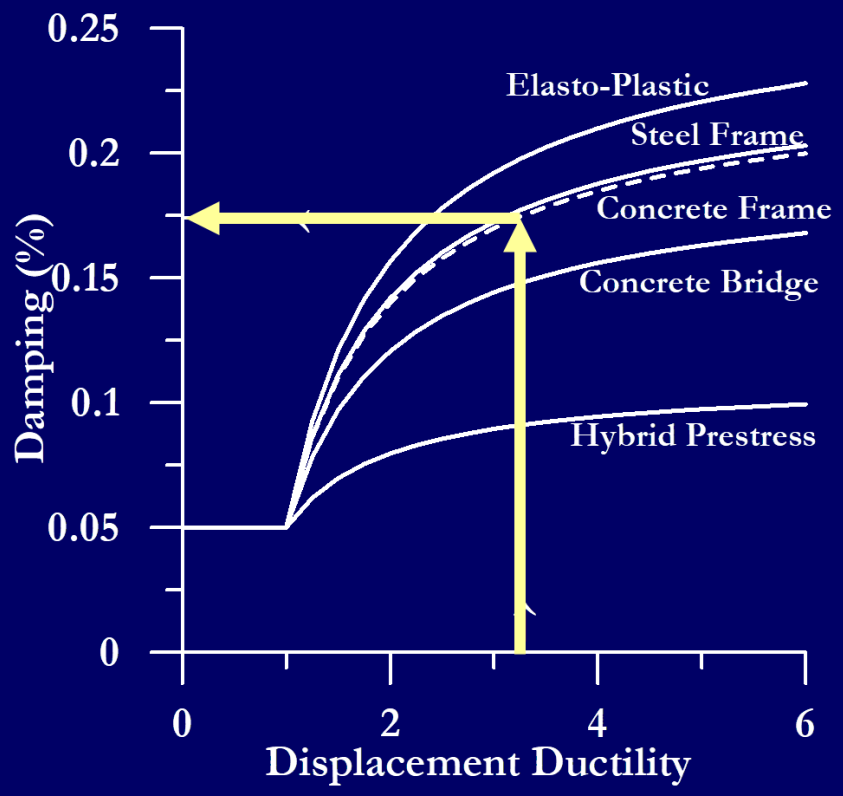
3.EQUIVALENT VISCOUS DAMPING

The design procedure requires relationships between displacement ductility and equivalent viscous damping.

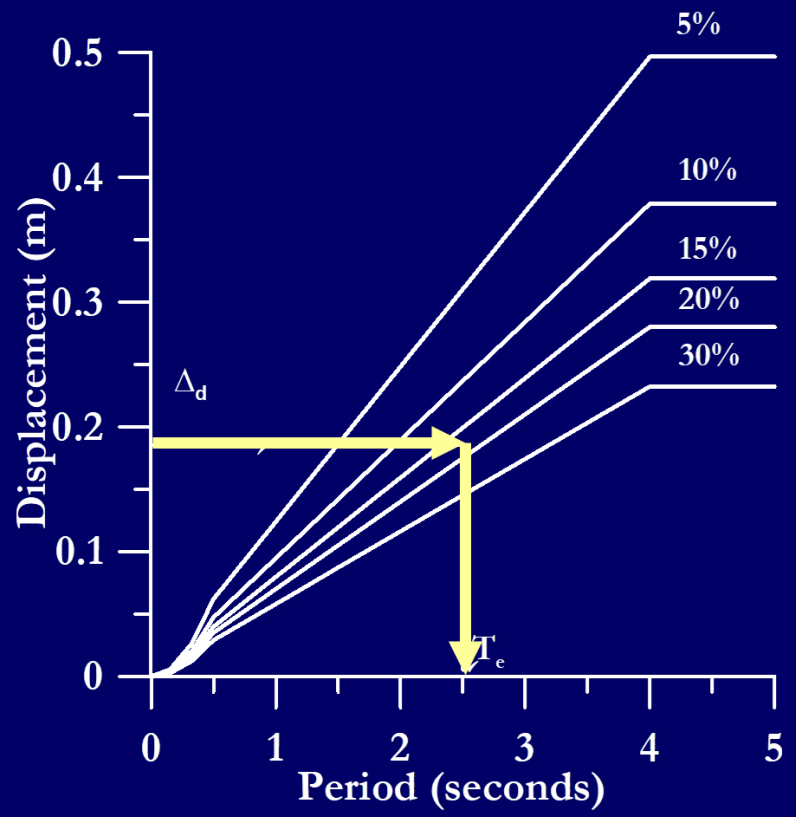
Damping is the sum of elastic and hysteretic damping, and is determined by inelastic time-history analysis for different hysteretic rules:

$$\xi_{eq} = \xi_{el} + \xi_{hyst}$$

Elastic damping, and the way that this has been modelled in time-history analysis in the past: refer Ch.4 pp 203-210 for details



(c) Equivalent damping vs. ductility

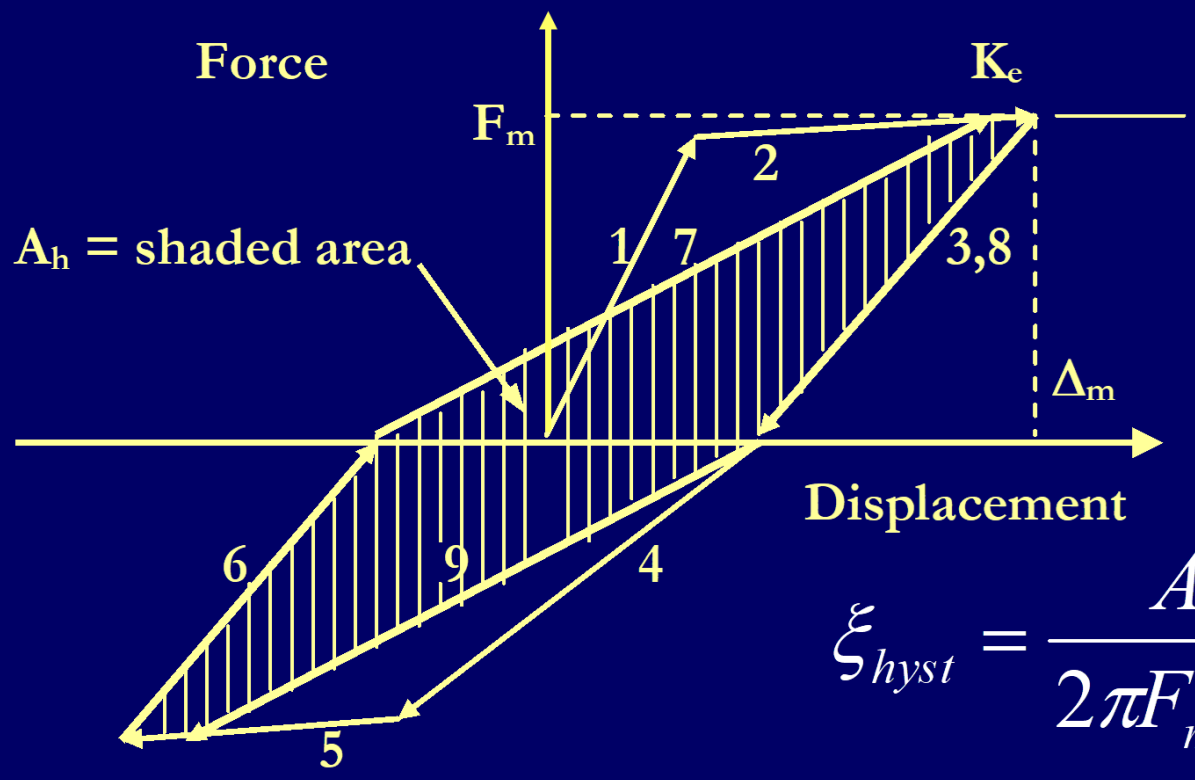


(d) Design Displacement Spectra

Limit State → Displacement; Ductility → Damping

Damping+Displacement → T_e; $K=4\pi^2 m_e/T_e^2$

HYSTERETIC DAMPING – INITIAL WORK: JACOBSEN EVD APPROACH



$$\xi_{hyst} = \frac{A_h}{2\pi F_m \Delta_m}$$

Worked OK for Takeda, but very non-conservative for "fat" hysteresis rules such as Elasto-plastic

RELATIONSHIPS FOR TANGENT-STIFFNESS DAMPING, T_e > 1 sec (CORRECTION FACTOR INCLUDED)

Concrete Wall Building, Bridges (TT): $\xi_{eq} = 0.05 + 0.444\left(\frac{\mu - 1}{\mu\pi}\right)$

Concrete Frame Building (TF): $\xi_{eq} = 0.05 + 0.565\left(\frac{\mu - 1}{\mu\pi}\right)$

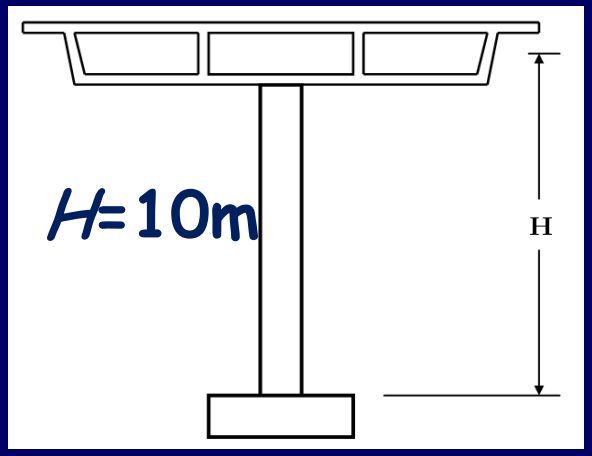
Steel Frame Building (RO): $\xi_{eq} = 0.05 + 0.577\left(\frac{\mu - 1}{\mu\pi}\right)$

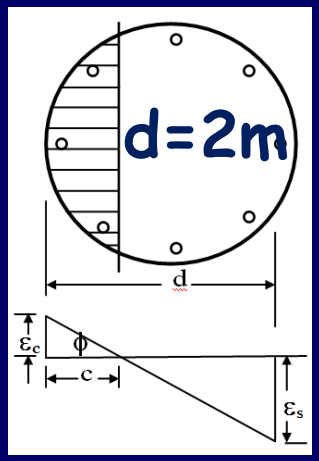
Hybrid Prestressed Frame (FS, β=0.35): $\xi_{eq} = 0.05 + 0.186\left(\frac{\mu - 1}{\mu\pi}\right)$

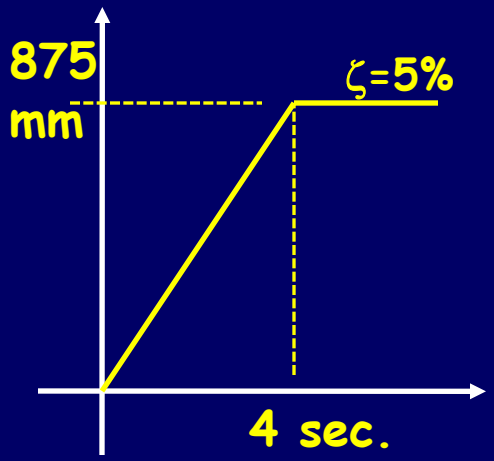
Friction Slider (EPP): $\xi_{eq} = 0.05 + 0.670\left(\frac{\mu - 1}{\mu\pi}\right)$

Bilinear Isolation System (BI, r=0.2): $\xi_{eq} = 0.05 + 0.519\left(\frac{\mu - 1}{\mu\pi}\right)$

Example - DDBD SDOF







f_y=470MPa
E_s=200GPa
W=5000kN
θ_d=0.035
μ_d=4

Target Displacement:

Drift: Δ_d=(0.035)(10m) = 0.350 m

Ductility: $\Delta_d=\mu_d\Delta_y$

$\Delta_y=\phi_y H^2/3$

$\phi_y=2.25\varepsilon_y/D$=0.00264 1/m

Δ_y= 0.088 m

Δ_d = 4(0.088) = 0.353 m

Example – DDBD SDOF

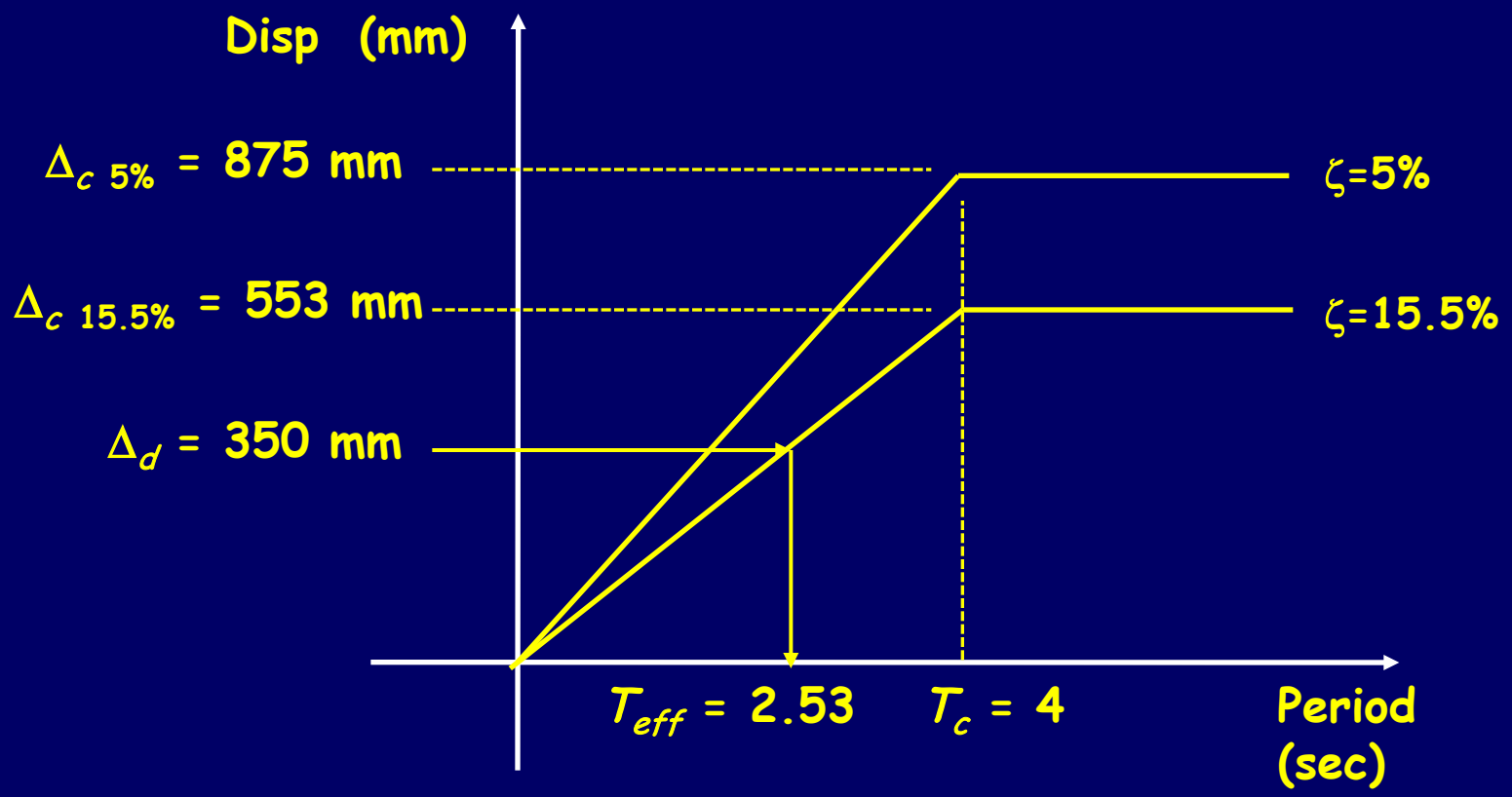
Equivalent Viscous Damping *(These expressions all assume 5% tangent stiffness proportional viscous damping and hysteretic damping)*:

Concrete Wall Building, Bridges (TT):	$\xi_{eq} = 0.05 + 0.444\left(\frac{\mu - 1}{\mu\pi}\right)$
Concrete Frame Building (TF):	$\xi_{eq} = 0.05 + 0.565\left(\frac{\mu - 1}{\mu\pi}\right)$
Steel Frame Building (RO):	$\xi_{eq} = 0.05 + 0.577\left(\frac{\mu - 1}{\mu\pi}\right)$
Hybrid Prestressed Frame (FS, β =0.35):	$\xi_{eq} = 0.05 + 0.186\left(\frac{\mu - 1}{\mu\pi}\right)$
Friction Slider (EPP):	$\xi_{eq} = 0.05 + 0.670\left(\frac{\mu - 1}{\mu\pi}\right)$
Bilinear Isolation System (BI, r =0.2):	$\xi_{eq} = 0.05 + 0.519\left(\frac{\mu - 1}{\mu\pi}\right)$

$$\xi_e = 0.05 + 0.444(3.97 - 1)/3.97\pi = 0.155 \quad (15.5\%)$$

Example - DDBD SDOF

***Obtaining Effective Period*:**



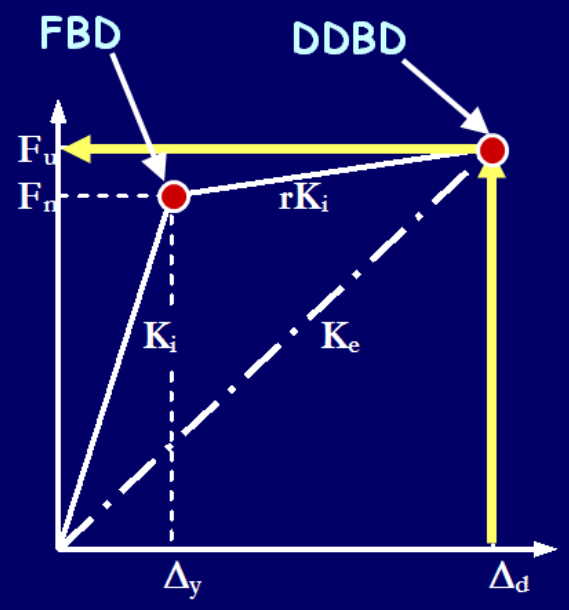
NOTE: $\Delta_{c\ x\%} = \Delta_{c\ 5\%}\ R_\xi$ $R_\xi = \sqrt{\dfrac{7}{2+\zeta}}$

Example – DDBD SDOF

Obtaining Effective Stiffness:

$$K_e = 4\pi^2 m_e / T_e^2 = 4\pi^2 5000/(9.805 \times 2.53^2) \quad = 3145 \text{ kN/m}$$

Obtaining Design Base Shear:

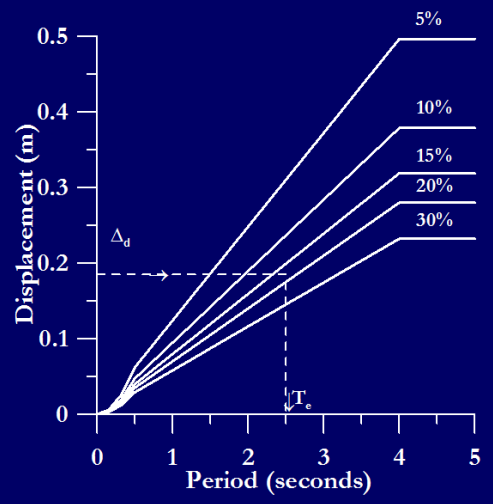


$$V_{Base} = K_e \Delta_d = 3145 \times 0.35 = 1100 \text{ kN}$$

Simplified Base Shear Equation for DDBD

$$V_{Base} = K_e \Delta_d = \frac{4\pi^2 m_e}{T_c^2} \cdot \frac{\Delta_{c,5}^2}{\Delta_d} \cdot \left(\frac{0.07}{0.02 + \xi} \right)^{2\alpha}$$

α = 0.5 for regular conditions
α = 0.25 for velocity pulse conditions
NOTE: Damping expressed as ratio in the above equation (not %).
NOTE: Equation assumes a linear DRS to the corner point.



Sample Problems
See Handout

Session 4

Longitudinal Design of Bridges

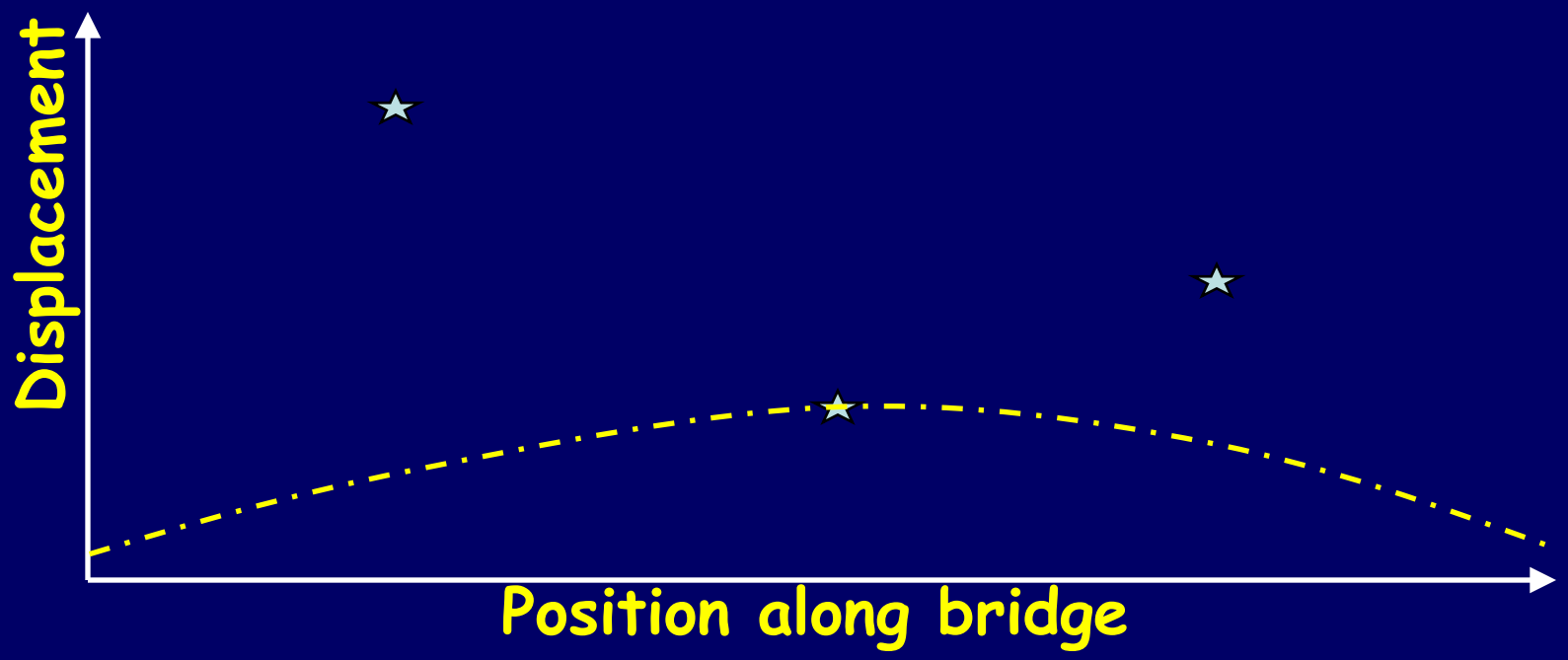
Transverse Design of Bridges

DDBD OF MDOF BRIDGES

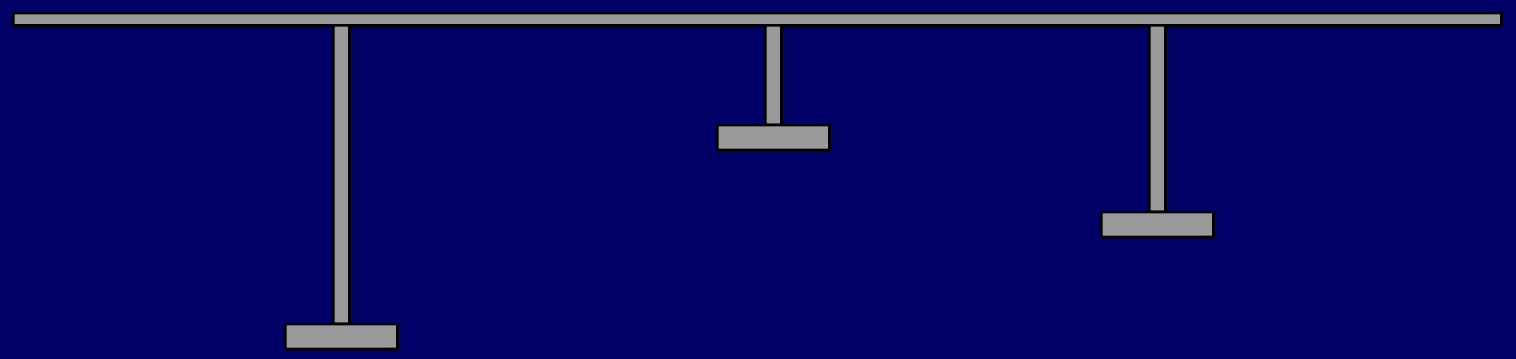
Longitudinal Design: If the bridge is straight, this is generally straightforward, but will often dominate design requirements. Effective damping and design displacement are the main issues.

Transverse Design: More complex, but often doesn't govern. Displacement shape may not be obvious at start. Design displacement, damping, higher mode effects need to be considered.

Obtaining Displaced Shape



Note: Stars are limit state displacements based on strain, ductility, or drift



System Displacement and Effective Mass

From work balance between MDOF and SDOF systems:

$$\Delta_d = \sum_{i=1}^{n}\left(m_i \Delta_i^2\right) / \sum_{i=1}^{n}\left(m_i \Delta_i\right)$$

From force equilibrium between MDOF and SDOF systems:

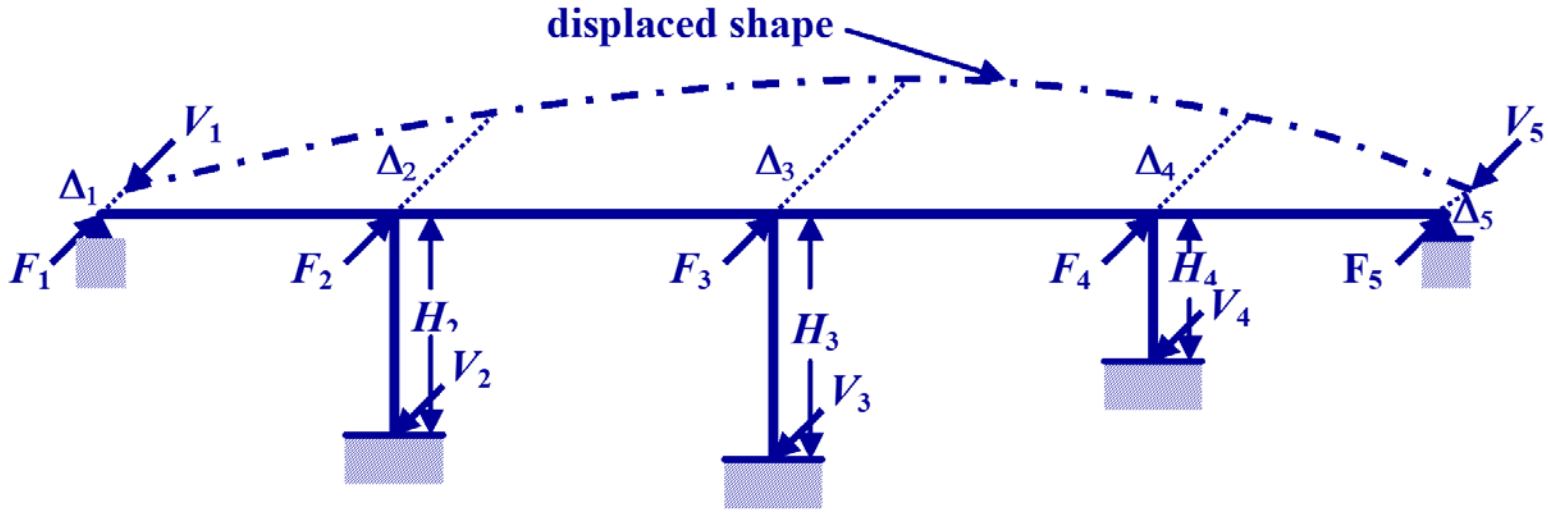
$$m_e = \sum_{i=1}^{n}\left(m_i \Delta_i\right) / \Delta_d$$

Base Shear Distribution

$$F_i = V_B\left(m_i \Delta_i\right) / \sum_{i=1}^{n}\left(m_i \Delta_i\right)$$

Force is distributed in proportion to mass and pier top displacement.

DAMPING COMPONENTS FOR BRIDGE

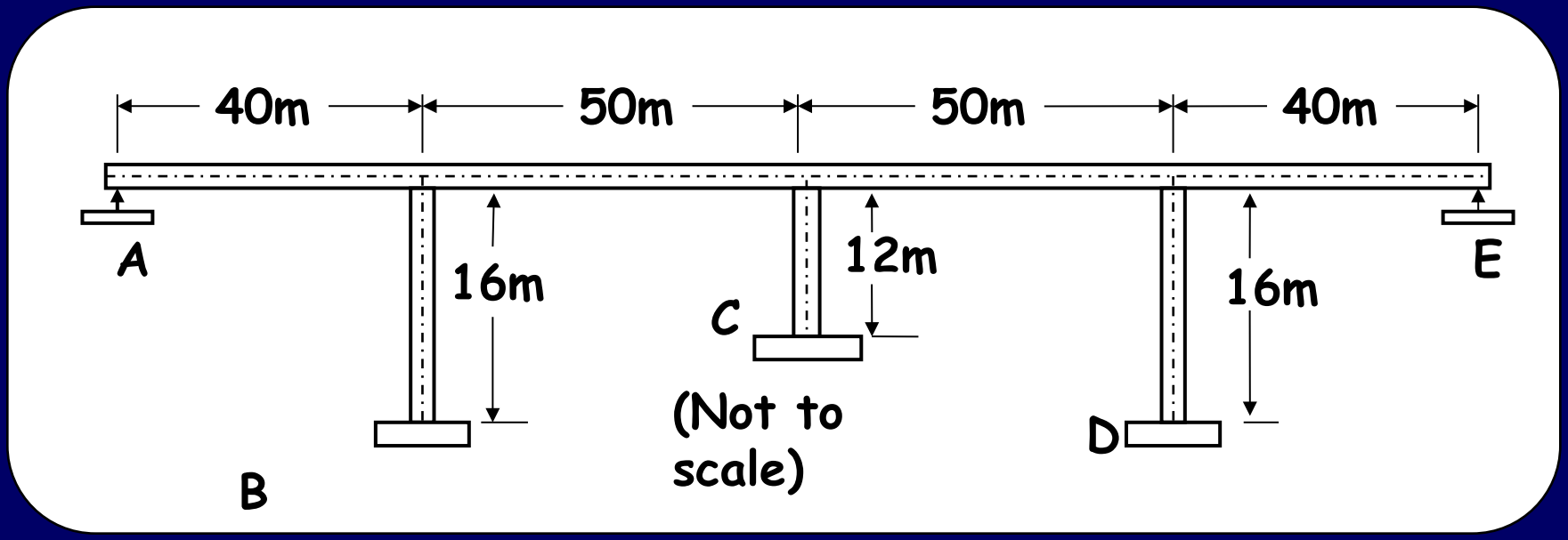


Pier Damping: $\xi = 0.05 + 0.444\left(\dfrac{\mu - 1}{\mu\pi}\right)$ **where** $\mu_i = \Delta_i / \Delta_{yi}$

System Damping:

$$\xi_e = \frac{x(\Delta_d - \Delta_a)\xi_{SS} + x\Delta_a\xi_a + (1-x)\left(\sum_{i=2}^{4}\frac{1}{H_i}\cdot\Delta_i\xi_i\right)\Big/\sum_{i=2}^{4}\frac{1}{H_i}}{x(\Delta_d - \Delta_a) + x\Delta_a + (1-x)\left(\sum_{i=2}^{4}\frac{1}{H_i}\cdot\Delta_i\right)\Big/\sum_{i=2}^{4}\frac{1}{H_i}}$$

Transverse Design Example



Estimate proportion of total force carried to abutments: X = 0.5
Target displaced shape (governed by limit state displacement of central column: 40mm; 417mm; 596mm; 417mm; 40mm

Pier B and D displacements are assumed to be 70% of Pier C displ.

Example, continued

System displacement: 485mm
Pier ductilities: 1.59; 3.82; 1.59
Pier damping: 10.2%, 15.4%, 10.2%
System damping: 8.9%
Base shear: 10280 kN
Lateral force distribution: 115; 2820; 4410; 2820;115 kN
Lateral analysis using secant stiffness properties:

43mm; 383mm; 572mm; 383mm; 43mm (actual)
40mm; 417mm; 596mm; 417mm; 40mm (target)

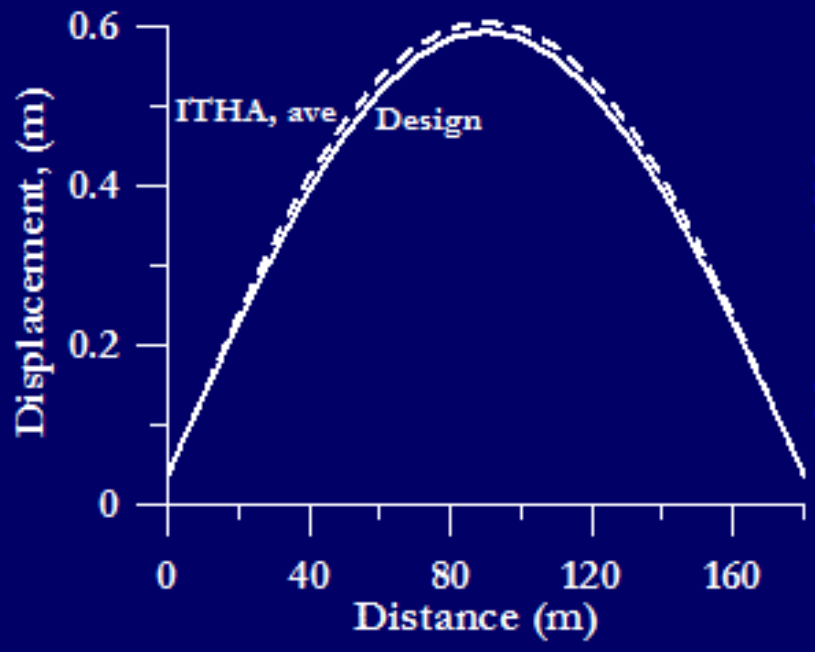
Revision of proportion of force carried by abutments.

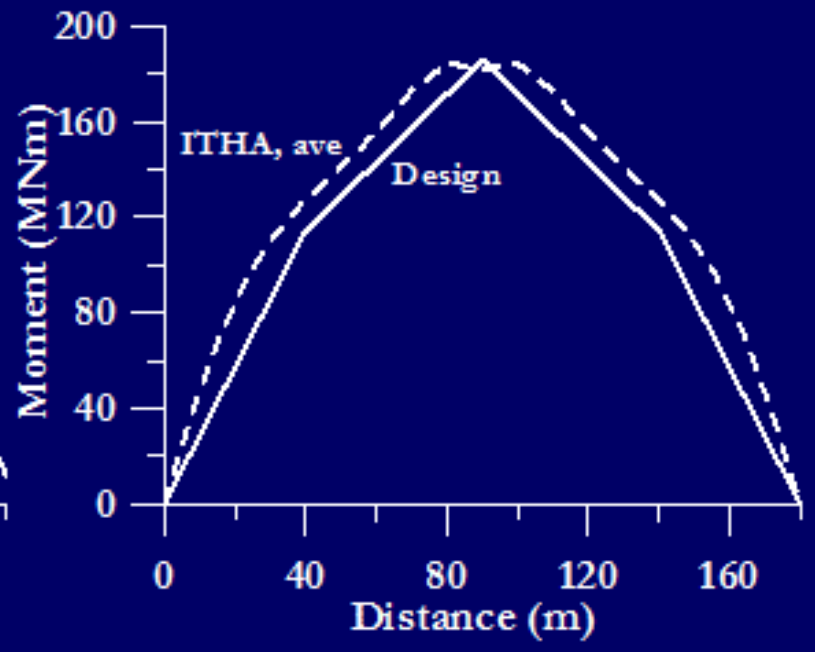
(increase portion of force to abutments slightly)

Converge onto X and displaced shape.

40mm; 395mm; 595mm; 395mm; 40mm (final)

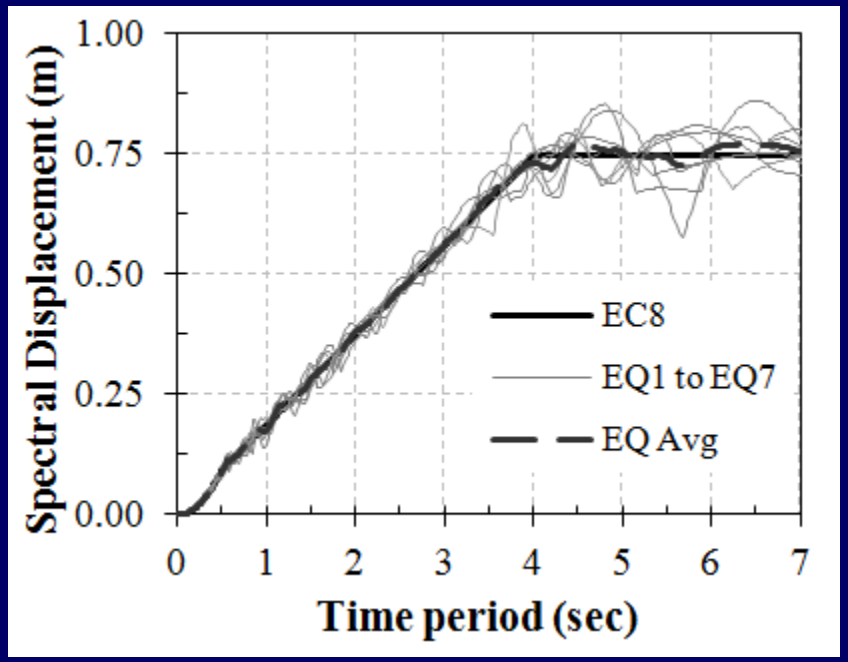
Sample Design and Analysis Result for MDOF Bridge



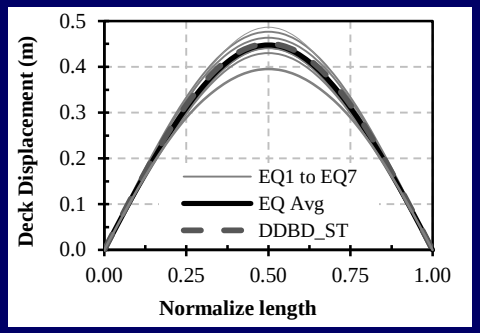


Other verification results

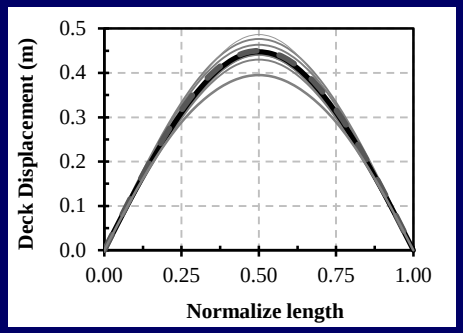
- 2, 4, 6 span bridges with 9 different support conditions.
- Each bridge designed with DDBD and then analyzed with NLTH analysis.



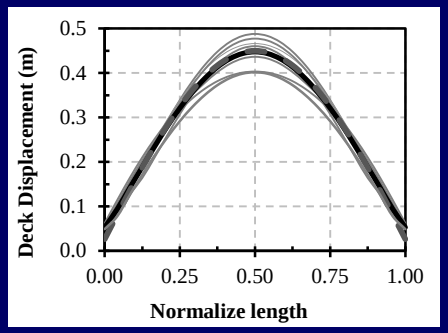
6 Span Bridge Results



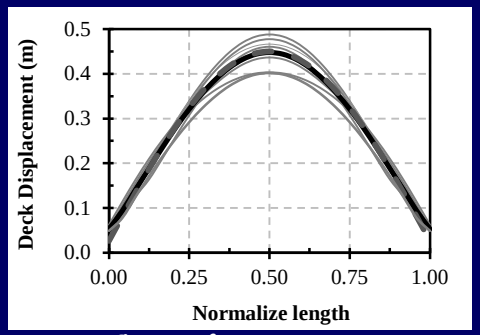
Case 1



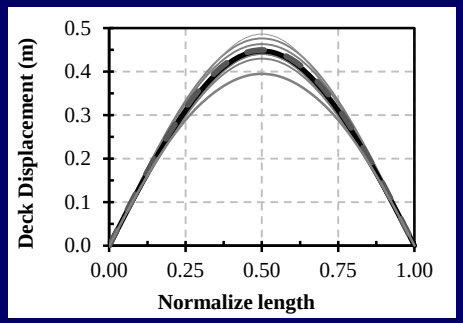
Case 2



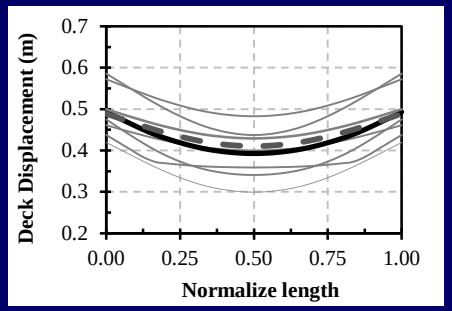
Case 3



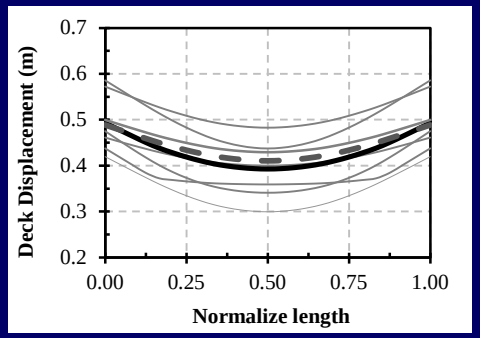
Case 4



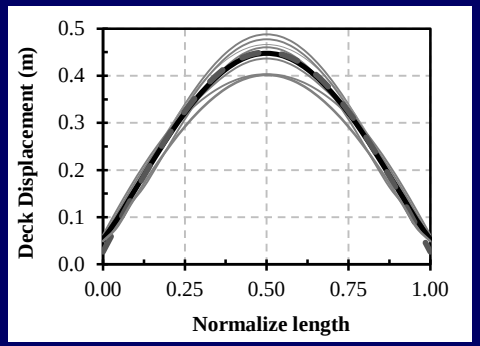
Case 5



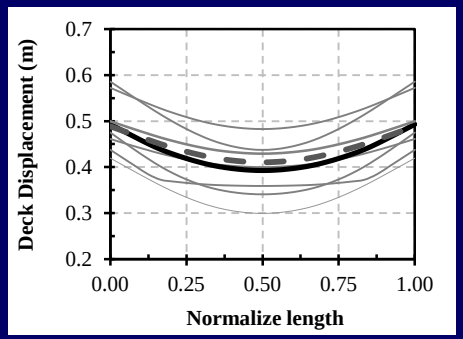
Case 6



Case 7



Case 8



Case 9

IMPLEMENTATION OF DDBD IN PRACTICE

CODES:

1. Chapter 14 is written in code format, as a starting point for code development.

2. Envisaged as being adopted as an "alternative" design process (i.e. parallel force-based and displacement-based procedures acceptable)

3. POLA has adopted DDBD as the preferred procedure of a dual force-based/displacement-based code (performance defined by limit strains for BOTH approaches.

4. Australia, New Zealand, Europe developing DDBD based codes.

IMPLEMENTATION OF DDBD IN PRACTICE

WITHIN EXISTING CODES:

- Many codes permit the use of Time-history analysis as a design tool, hence:

1. Design using DDBD to obtain a rational design
2. Verify response using ITHA.

Note that this approach follows the logical procedure of using analysis to verify design, rather than using analysis to DEFINE design (as with multi-modal analysis)

To learn more

- Textbook/papers
- Occasional short courses
- Feel free to contact me with any questions or to chat further.

Panelists Presentations

http://onlinepubs.trb.org/onlinepubs/webinars/170622.pdf

After the webinar, you will receive a follow-up email containing a link to the recording

Today's Participants

- Elmer Marx, *Alaska Department of Transportation and Public Facilities,* elmer.marx@alaska.gov
- Mervyn Kowalsky, *North Carolina State University,* kowalsky@ncsu.edu

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